Experimental Investigations on the Dissolved Gas Analysis Method (DGA) through Simulation of Electrical and Thermal Faults in Transformer Oil

Dissertation

zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften
Dr. rer. nat.

vorgelegt von

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2014

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This research work was developed during the period from June 2005 to October 2008 at the Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart, under the supervision of Prof. Dr.-Ing. Stefan Tenbohlen.

I declare that this dissertation represent my own work, except where due acknowledgement is made.

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Jackelyn Aragón Gómez

“Reach high, for stars lie hidden in you. Dream deep, for every dream precedes the goal.”

— *Rabindranath Tagore*

Acknowledgment

I am greatly thankful of Prof. Dr. Oliver Schmitz, Head Director of the Institute of the Applied Analytical Chemistry and Prof. Dr.-Ing. Holger Hirsch, Head Director of the Institute of Electrical Power Transmission at the University of Duisburg-Essen, for their willingness to review and examine my dissertation in spite of the time constraints and giving worth to my efforts of years. I deeply appreciate their professional and constructive approach towards my research work. I would like to mention very special thanks to Prof. Dr. Mathias Ulbricht, Head Director of Institute of Technical Chemistry for his encouragement, trust and support.

There are no word to express my deepest gratitude to my loving husband, Dr.-Ing. Sachin Ramesh Patil, he did not only encourage me throughout the research and writing of the dissertation, but he also patiently endured the seemed never-ending discussions on the topics of this work. I deeply appreciate the enlightening ideas and useful inputs that he has provided using his objective perspective and scientific background. I sincerely acknowledge his help for organizing and editing this dissertation for countless times. Without him in my life, I would not have been able to accomplish this endeavor.

I am thankful of the technical supervision and financial support provided by Prof. Dr.-Ing. Stefan Tenbohlen, Head Director of the Institute of Power Transmission and High Voltage Technology (IEH) at the University of Stuttgart. I am grateful to my colleagues and staff of IEH with whom I shared those times of conducting laboratory experiments at the University of Stuttgart. Their great attitude of cooperation and camaraderie made a pleasant working environment. My special thanks to the students, for their sincere engagement and intellectual input to this research work. Moreover, I convey my sincere gratitude to the workshop staff, Mr. Rönish, Mr. Beck and Mr. Schill, whose creative skills and cooperation made the challenging construction of experimental setups possible. I would like to acknowledge the kindness and diligence of Dr. Schärli, Mrs. Schärli and Mrs. Lwowski, who helped me in many organizational aspects.

I sincerely acknowledge the cooperation and internship offered by Siemens AG, Nürnberg. I am thankful of Kelman Ltd. U.K., GATRON GmbH, and ECH Elektrochemie Halle GmbH and Energy Support GmbH for providing the necessary measurement equipments and technical support.

I express my deep gratitude and love for my mother, father, relatives and friends, who have wished me the strength, health and courage to accomplish the work. They have been always there to express their love and support

regardless of the distance and time.

Last but not least, very loving thanks to my wonderful son Arjun for the motivation and energy he provided me in the difficult times with his cheerful smile. He is the most precious gift in my life.

Finally, I am would like express me sincere thanks to everyone that in one or other way have encourages and supported me to bring this odyssey to its end, including Ms. Martyna Gajda for the last minute help for translation.

This marvelous opportunity has revealed me once again, that regardless of any obstacles there is always a fair chance for those who has courage to seek for it, and that one should never give up a goal. Thanks dear God, for your providence.

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Abstract

Gas generation in transformer oil is induced by electrical and thermal faults resulting from unfavorable operating conditions in transformers. Along with aged conditions of transformers, operating factors such as high temperature, strong electrical fields, electrical discharges, mechanical stresses, insulation damage and contaminants pose imminent risks of malfunctioning and irreversible damage to the transformers. Transformer monitoring methods based on dissolved gas analysis (DGA) have gained great significance and attention in order to ensure timely and accurate diagnostics of the electrical and thermal faults occurring in the transformers. Gases that act as fault indicators are hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide and dioxide.

The dissolved gas analysis (DGA) has been widely acknowledged as an effective and rather simple method for fault diagnostic of transformers. However the diagnostic of the faults by DGA directly depends on the knowledge about gas generation patterns produced by various types of faults. Moreover, the reliability of the diagnostic depends considerably on the technics of gas-in-oil extraction and analysis as well as the procedures for oil sampling and storage.

The undertaken experimental investigations were aimed at understanding the process of gas generation due to electrical or thermal faults in transformers and assessing the commercially available gas-in-oil measurement technics in order to enhance the application of the dissolved gas analysis (DGA) method. For that purpose experiments were carried out by simulating electrical and thermal faults in laboratory setups equipped with DGA monitoring technics that allowed verification of gas genetaion pattern due to specific type of faults. Additionally, the effects of oil sampling and gas-in-oil measurement technics as well as the diffusion flux of fault gases-in-oil on the results of DGA were also investigated.

During these investigations four techniques for extraction of dissolved gases were evaluated. Results of gas-in-oil analysis revealed that an automated DGA monitoring system consisting of a vacuum extraction device and gas chromatography provides the most efficient extraction and precise concentrations of gases. It was observed that air bubbles entering the oil due to

improper sampling and storage significantly decrease the hydrogen concentration. Exposure of oil samples to light and higher temperatures leads to generation of hydrogen due to faster oxidation rates. It was demonstrated that storage of oil samples in air-tight container, in darkness and constant ambient conditions can provide reliable gas-in-oil measurements for a storage period up to 16 days. The effect of 'stray gassing' in oils, which is characterized by generation of hydrogen in high concentration, was also documented during the investigations. These observations point to the potential sources of errors in DGA.

An extensive part of this research work was focused on constructing experimental setups to produce thermal and electrical faults as in the power transformers. The construction of a small scale setup (30 kV and 12 liter oil tank) and a large scale setup (100 kV and 600 liter oil tank) including oil tanks, oil circulation system, high voltage system, and control panel was accomplished with necessary details. The experimental setups allowed the simulation of electrical and thermal faults in transformers, under controlled parameters such as current, voltage, temperature and oil conditions.

The small scale setup was used for simulating the partial discharges (PD) fault and hotspots (HS) faults of different temperatures in transformer oil. The setup allowed the investigations of the fault gas generation process by means of various commercially available DGA monitoring techniques.

The large scale experimental setup, which includes oil tank, conservator tank as well as oil circulation and reconditioning system, provided an enhanced model of an air-breathing power transformer. It was also equipped with an automated system to control valves and pumping rates of oil circulation and reconditioning system, as it occurs in a power transformer for cooling purpose. The large scale setup was employed for simulating intense arcing discharge (AD) faults at high voltage levels.

The gas concentrations obtained for the three types of faults (PD, HS and AD) were interpreted using the fault interpretation scheme CIGRE TF 15.01.01 (CIGRE scheme), which is one of the latest DGA interpretation schemes. The interpretations suggest that the CIGRE scheme provides inconsistent diagnostic of PD and HS faults, otherwise it seemed to be consistent in diagnosing AD faults. Based on the overall results it was concluded that the CIGRE scheme should be applied cautiously and additional factors must be considered for a reliable diagnostic. The graphical DGA interpretation method, so called gas generation pattern method, resulted to be sufficiently reliable at the diagnostics of PD, HS as well as AD faults. This method exhibits great potential to be utilized for fault diagnostics as a separate method or in com-

bination with the CIGRE scheme.

The large scale setup was also used for investigating the continuous diffusion of fault gases from oil into the atmosphere via the air-breathing conservator tank. The investigations confirmed that the diffusion process has a strong influence on the diagnostics of faults using DGA. The diffusion of gases leads to an underestimation gas-in-oil concentrations and consequently incorrect fault diagnostics. The diffusion flux of gases tends to increase at higher oil circulation rates, especially for highly volatile fault gases, such as hydrogen.

Kurzfassung

Die Gasentstehung in Transformatorölen wird durch elektrische und thermische Fehler verursacht, welche zu ungünstigen Betriebsbedingungen in Transformatoren führen. Mit dem Alterungsprozess des Transformators gehen ungünstige Betriebsfaktoren wie erhöhte Temperaturen, starke elektrische Felder, elektrische Entladungen, mechanischer Stress und Schäden der Isolation einher, welche zur Verstärkung jener fehlerhaften Betriebsbedingungen und dementsprechend zu stärkerer Gasentstehung führen und somit das akute Risiko für irreversible Schäden oder eine Explosion erhöhen. überwachungs- und Diagnosemethoden, die auf der Dissolved Gas Analysis (DGA) basieren, haben aufgrund ihres Einsatzpotentials zur kontinuierlichen und zuverlässigen Erkennung von Transformatorenfehlern, große Bedeutung und Aufmerksamkeit gewonnen. Einige der im Transformatoröl gelösten Gase können als Wasserstoff, Methan, Ethan, Ethylene, Acetylen, Kohlenmonoxid und Kohlendioxid identifiziert werden.

Die Dissolved Gas Analsysis (DGA) ist als effektive und einfache Methode zur Fehlerdiagnose in Transformatoren anerkannt. Allerdings beruht die Fehlerdiagnose der DGA auf dem Wissen über die Zuordung der einzelnen Gasmuster zu den verschiedenen Fehlern in Transformatoren. Darüber hinaus hängt die Zuverlässigkeit der Fehlerdiagnose beträchtlich von der Technik der Gas-in-Öl Extraktion und Analyse, sowie der Probenentnahme und Probenlagerung ab. Die durchgeführten experimentellen Untersuchungen hatten das Ziel zu verstehen, wie die elektrischen und thermischen Fehler die Gasentstehung verursachen und die herkömmlichen Gas-in-Öl Messungen einzuschätzen, um die Anwendungen der DGA zu verbessern. Zu diesem Zweck wurden Experimente durchgeführt, in denen elektrische und thermische Fehler in Transformatoren simuliert worden sind. Dabei waren die Versuchsaufbauten mit verschiedenen DGA-überwachungstechniken ausgestattet, so dass die Gasmuster kontinuierlich verifiziert werden konnten. Zudem wurde untersucht welchen Effekt die Probenentnahme und die Art der Durchführung der Gas-in-Öl Messung sowie der Diffusionsfluss der entstehenden Gase auf die DGA-Ergebnisse hatten.

Während dieser Untersuchungen wurden vier Techniken für die Extraktion von gelösten Gasen getestet. Die Ergebnisse der Gas-in-Öl Analyse zeigten, dass eine automatische DGA-überwachungstechnik, die aus einer Vakuumex-

traktionsanlage und einem Gaschromatograph besteht, die effizienteste Extraktion und die genausten Gaskonzentrationen erbringt. Des Weiteren wurde beobachtet, dass eine falsche Probenentnahme und Lagerung dazu führt, dass Luftblasen in die Probe diffundieren, welche die Wasserstoffkonzentration im Öl verminderten. Werden die Ölproben Licht und hohen Temperaturen ausgesetzt, so wird aufgrund eines schnelleren Oxidationsprozesses mehr Wasserstoff im Öl erzeugt. Es konnte bewiesen werden, dass bei Lagerung der Probe in luftdichten Behältern wie Glasspritzen, in Dunkelheit und bei konstanten äußeren Bedingungen bis zu 16 Tagen zuverlässige Gas-in-Öl Erg- ebnisse geliefert werden. Der Effekt des Stray Gassing in Öl, welcher mittels der höheren Wasserstoffkonzentration charakterisiert wurde, ist während der Untersuchungen ebenfalls dokumentiert worden. Diese Fakten deckten potentielle Fehlerquellen in der DGA Anwendung auf.

Ein großer Teil dieser Arbeit befasste sich mit dem Aufbau von experimentellen Versuchsanordnungen, um thermische und elektrische Fehler wie Teilentladungen, Durchschläge und Hotspots zu simulieren. Dafür wurde ein kleiner maßstabgerechter Versuchsaufbau (30 kV und 12 Liter Öl) und ein großer maßstabsgerechter Versuchsaufbau (100 kV und 600 Liter Öl) konstruiert. Diese beinhalteten einen Öltank sowie ein Ausdehnungsgefäß, einen Ölkreislauf, Hochspannung und ein Steuerungssystem, die einem Leistungstransformator nachempfunden waren. Mittels dieser Versuchsaufbauten war es möglich, unter kontrollierten Parametern wie Stromstärke, Spannung, Temperatur und Ölbedingungen, die elektrischen und thermischen Fehler im Öl zu erzeugen.

Der kleine Versuchsaufbau wurde zum Einsatz des Teilentladungsfehlers, sowie des Hotspotfehlers von verschiedenen Temperaturen angewendet. Dieser Aufbau ermöglichte die Untersuchung von gelösten Gasen mit markverfügbaren DGA-überwachungstechniken.

Der große Versuchsaufbau, welcher Öltank, Ausdehnungsgefäß sowie einen Ölkreislauf enthielt, stellte ein verbessertes Model des atmenden Transformators dar. Zudem war dieser mit einem automatischen System zur Kontrolle der Ventile und der Pumpgeschwindigkeit des Ölreislauf ausgestattet, so wie es in dem Leistungstransformator zur Kühlung vorkommt. Dieser große Versuchsaufbau wurde zur Simulation von elektrischen Durchschlagentladungen bei höheren Spannungspegeln angewendet.

Die entstandenen Gaskonzentrationen für die verschiedenen Fehlertypen (Teilentladung, Durschlag und Hotspot) wurden mittels eines der aktuellsten DGA-Interpretationsschemas CIGRE TF 15.01.01 ausgewertet. Die Fehlerinterpretation der Gaskonzentrationen deutet darauf hin, dass das CIGRE

Schema unbeständige Diagnostik für Teilentladungen und Hotspot lieferte. Anderseits schien es, dass das CIGRE Schema zuverlässig in der Diagnostik von elektrischem Durschlag ist. Basiert auf diesen Ergebnissen wurde festgestellt, dass dieses DGA-Interpretationsschema mit Bedacht angewendet werden sollte und zusätzliche Methoden für eine zuverlässige Fehlerdiagnostik mit einbezogen werden sollten. Des Weiteren stellte sich heraus, dass die graphische DGA-Interpretation, die sogenannte Gasentstehungsmuster Methode, zur zuverlässigen Diagnostik von Teilentladungen, elektrischem Durschlag sowie Hotspot, geeignet ist. Diese Methode zeigte großes Potential als separate DGA-Interpretationsmethode oder zusammen mit dem CIGRE Schema, zur Fehlerdiagnostik angewendet zu werden.

Mittels des großen Versuchsaufbau war es möglich die kontinuierliche Gasdiffusionsrate von Öl in die Luft über das atmende Ausdehnungsgefäss zu untersuchen. Die Untersuchungen bestätigten, dass der Diffusionsprozess einen starken Einfluss auf die DGA-Fehlerinterpretation hat. Die kontinuierliche Gasdiffusion führt zu einer Unterschätzung der Fehler Gaskonzentrationen und damit zu falsche Fehlerdiagnose. Der Diffusionsfluss neigt dazu, mit schneller Ölzirkulationsraten zu erhöhen, speziell für hochflüchtigen Fehlergase, wie Wasserstoff.

1 Background and Objectives of the Research

1.1 Description of the problem

Power technology has been passing through great challenges in the attempt to cope with the ever-growing world energy demand. Nonetheless, the technology of oil-filled transformers has remained almost unchanged for about a century. At present there is a large fleet of transformers exposed to different cumulative stresses which eventually are approaching the end of their expected lifespan. Consequently, many of these transformers would need to be replaced or repaired to safeguard power supply. However many power agencies are shifting their attention to monitoring and diagnostic methods, that can provide a reliable assessment of the transformer condition. In that trend, online monitoring techniques based on the dissolved gas analysis (DGA) have gained great importance as a continuous and non-invasive method, but still there are cost and technical limitations of these monitoring techniques, regarding their accuracy at diagnosing faults in transformers.

The actual average age of transformer fleets in developed countries have surpassed 30 years, which was the limiting life-span designed for these transformers in order to operate safely and reliably [TD-World, 2007]. Moreover the deregulation of the energy market has forced power agencies to avoide investments on new transformers and to utilize their currently installed electrical components at their full capacity, over longer distances and periods in order to minimize service costs. Thus, an increased concern about the current condition assessment of transformers has arisen implementation of maintenance strategies and condition monitoring techniques. An effective detection of the faulty conditions in transformers through condition strategies can prolong their technical lifespan and prevent costly breakdowns [Nynas Naphthenics, 2004].

The transformers operating under the present power loads are highly prone to develop the type of faults that can lead to high outage costs as well as fire or explosions. Unfavorable operating conditions due to high temperature, strong electrical fields, electrical discharges, mechanical stresses, insulation

damage and contaminants can expose a transformer, regardless of its age, to imminent and irreversible damage.

Need for assessment of oil condition

Until the date, the combination of transformer oil and cellulose paper has remained the most effective insulating system due to their excellent dielectric strength and relatively low cost. However, the transformer oil undergoes the oxidation process due to free radical reactions between unstable hydrocarbon molecules and oxygen. This reactions are catalyzed in presence of copper and iron in transformer, and further accelerated due to the heat dissipated from windings and the core. The oxidation of the oil leads to loss of its dielectric strength and generate wide range of solid, liquid and gaseous compounds. These compounds can further trigger the development of faults in the transformer.

Under normal operating conditions of a transformer, the oil is subjected to a continuous oxidation process at slow rate. However, the oxidation process can abruptly accelerate due to higher-than-usual amount of energy dissipated by an electrical or a thermal fault in the transformer, leading to a sudden increase in the concentrations of certain hydrocarbon gases and other compounds. Thus, the condition of the transformer oil, which include concentrations of dissolved gases, presence of sludge particles, color etc. provides useful information about the technical state of the transformer and its malfunctioning.

Dissolved gas analysis of oil (DGA)

Transformer oil serves as a carrier of the information from which possible abnormal operating conditions in a transformer can be detected. This is achieved by carrying out dissolved gas analysis (DGA). The dissolved gas analysis is a well acknowledged technique useful for the detection of incipient faults in transformers [Nynas Naphthenics, 2004]. The DGA consists of sampling of oil from a service transformer under consideration, extraction of the gases dissolved in the oil sample and quantitative analysis of concentrations of characteristic fault gases by means of analytical techniques. The characteristic fault indicator gases are hydrogen, methane, ethane, ethylene, acetylene, carbon dioxide and carbon monoxide. The DGA can be carried out as a routine test in laboratory, or continuously by using online DGA monitoring .

The essential part of DGA lays on the gas-in-oil analysis and interpretations for a reliable fault diagnostic. Though the mechanisms of gas generation are

very complex and not yet fully understood, the patterns of gas generation corresponding to the types of faults are established on the basis of practical experiences [Sanghi, 2003]. The patterns of gas generation are usually represented in terms of thresholds of gas concentrations or key gas ratios pertaining to the types faults. Thus, the comparison of the concentration of the characteristics gases in the oil sample with the established thresholds and key gas ratios may help to detect whether a certain type of fault has occurred in the transformer, or any incipient fault is developing, or the transformer is working under normal condition.

Factors affecting the dissolved gas analysis

Over the last three decades, a great deal of research has been carried out to improve the DGA and its interpretation schemes. However, the reliability of the DGA methods is limited due to several factors related to: lack of knowledge about diffusion process of gases, the sampling of service oil, stray gassing behavior, techniques of dissolved gas extraction, techniques of gas measurement and the lack of sufficient knowledge about patterns of gas generation due to various types of faults.

Due to free interface between transformer oil and the surrounding atmosphere, located in the conservator of an air-breathing transformer, there is a continuous diffusion of fault gases from oil into the air. Depending on the interval of sampling, this process may have certain impact on DGA result. However, due to lack sufficient knowledge none of the present DGA methods address the impact of the diffusion process.

Though recommendations given by the international standard IEC 60567 about the proper conduction of oil sampling and analysis of dissolved gases, in the practice these instructions are often neglected due to lack of awareness about the influence of the sampling related factors, such as air-trapping, light, temperature etc., on the quality of DGA results. Moreover, the effect of stray gassing (an abnormal gassing behaviour of certain types of oils under normal operating temperatures) on DGA is usually not considered during the dissolved gas analysis.

There are several commercially available techniques for extraction of dissolved gases and their measurements. The commonly used techniques for DGA include vacuum gas extraction and gas chromatography. The efficiency of the gas extraction and precision of gas measurements have direct impact on the DGA results. The erroneous DGA results can lead to false interpretations of a fault in a transformer.

Several methods such as CIGRE interpretation scheme, key gas analysis, IEC ratio etc. have been proposed to interpret the DGA results to identify the types of faults and the condition of a transformer. However, the interpretations based on these schemes are often inconsistent and highly dependent on the additional information such as the history of transformer operation, experience of the interpreter etc. The experience gained by using these methods indicates that these methods are characterized by certain limitations, e.g. none of the methods is able to recognize slowly developing low energy faults or simultaneously occurring faults. Moreover, the presently used interpretation schemes do not provide any information regarding the intensity of the faults [Sun et al., 2012].

1.2 Research objectives

This research project is aimed at evaluating the factors affecting the dissolved gas analysis (DGA) through experimental investigations of the fault gas generation. Laboratory scaled models of the transformer oil tank including oil circulation piping system and high voltage system, which were used to simulate electrical and thermal fault, form the basis of the investigations. This research was further aided by the availability of more than one commercially available DGA techniques.

The specific objectives of this research project were defined as:

- Evaluation of factors affecting the gas-in-oil analysis, including gas extraction techniques, oil sampling and sample storage practices.
- Conduction of faults such as partial discharge (PD), arcing discharge (AD) and hotspot (HS) of various intensities by means of experimental setups designed to resemble fault conditions as in power transformers.
- Assessment of the fault gas generation triggered by electrical and thermal faults using DGA techniques that aimed at verifying the gassing behavior of oil under each fault type.
- Comparative analysis of different DGA interpretation schemes aimed at evaluating uncertainties involved in the application of fault interpretation schemes.
- Investigation of the diffusion process of fault gases from oil into the atmosphere through the open conservator tank, and the effect of circulation rate on the diffusion process.

2 Power Transformers and Dissolved Gas Analysis of Oils

The electrical power has been essential for the development of the modern society. The reliable supply of electricity has become not only essential for industrial, commercial and residential sectors but also a duty of governments. In the alternating current (AC) electrical supply systems transformer is an indispensable component. In a normal power generation plant electricity is generated at about 11000-15000 volts (11-15 kV). In distribution network it is passed to the first transformers to step up the voltage to the transmission level at approximately 220 to 500 kV. At the end of transmission route the voltage is stepped down to a sub-transmission level at about 33 kV to 132 kV. Then it is sent to distribution utility substations where the voltage is reduced to approximately 11 kV to 22 kV. Finally, the electric power with reduced voltage is sent to local transformers where it is further stepped down to the consumer voltage level of 415 V to 240 V [Harlow, 2004]. Several transformers are placed between power plant and consumers, which perform the important role of transforming the generated power to higher and/or lower voltage levels according the requirements.

Generally high voltages up to 750 kV are achieved in power distribution networks using power transformers, with the primary objective to reduce transmission losses by means of reducing the current required to be carried for the transmission of a given electrical power. This is achieved by means of power transformers of different voltage ranges incorporated within the power distribution system. Currently, transformer units of 1500 kV voltage rating are implemented on experimental basis [Harlow, 2004].

2.1 Power transformers

Since its first patent the transformer has been re-engineered to improved its functioning, consequently transformers have become more powerful and smaller over the years. The invention of oil-cooled transformers using oil and cellulose paper as insulating system opened the possibility to handle higher loads and voltage levels [Verma, 2005]. In spite of many technological ad-

vances in the design of transformers, the key materials used in transformers (copper, steel, oil and cellulose paper) are still the same. However, they are now improved and adapted for performance at much higher loads [Krawiec, 2009].

A transformer is basically a static electrical device that permits the transfer of alternating current (AC) or voltage between two electric circuits, based on the principles of electromagnetism and electromagnetic induction. The principle of electromagnetism states that an electric current passing through windings generates a magnetic field in the core. The principle of electromagnetic induction states that a variation of current in the primary winding will cause a change in the magnetic field which will induce a voltage through the secondary winding [Sadiku, 2006].

Basic technical concept

The core of a transformer is represented in figure 2.1. A simplified concept of a transformer consists of two electrically insulated windings: primary and secondary windings, supported by an iron core. The windings are insulated from each other as well as from the core. The number of turns determines whether the transformer can be used for stepping-up or stepping-down of the voltage. In a step-up transformer the secondary winding has higher number of turns as compared to the primary winding, and in a step-down transformer the secondary winding has less number of turns as compared to the primary winding.

The voltage induced in the secondary winding follows the Faraday's law of induction, which states, "*the electromotive force in any circuit is directly proportional to the time rate of change of magnetic flux through the circuit*" [Sadiku, 2006].

$$V_s = N_s \frac{d\Phi}{dt} \tag{2.1}$$

where,

V_s instantaneous secondary voltage

N_s number of turns of the secondary winding

Φ the magnetic flux through one turn of winding

Moreover, the cross section area 'A' is constant and the magnetic field changes with the time depending on the excitation of the primary winding. The same magnetic flux Φ passes through the primary and secondary windings

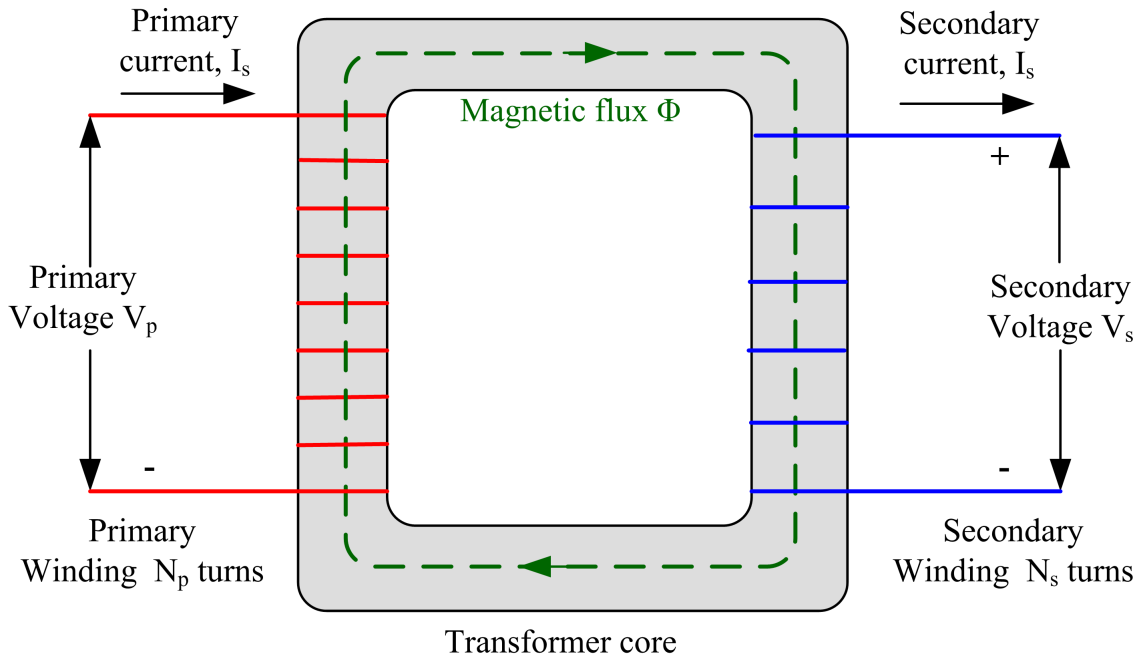

Figure 2.1: Core of a step-down transformer

[Sadiku, 2006], therefore the instantaneous voltage on the primary winding is given as:

$$V_p = N_p \frac{d\Phi}{dt} \tag{2.2}$$

where,

V_p instantaneous primary voltage

N_p number of turns of the primary winding

Then the voltage in secondary winding of a stepping up and stepping down transfromer can be calculated as following [Harlow, 2004]:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \tag{2.3}$$

where,

V_s instantaneous secondary voltage

N_s number of turns of the secondary winding

In an ideal transformer the electrical power is completely transmitted from the primary to the secondary winding and therefore the incoming electrical power equals the outgoing electrical power, as shown in figure 2.2.

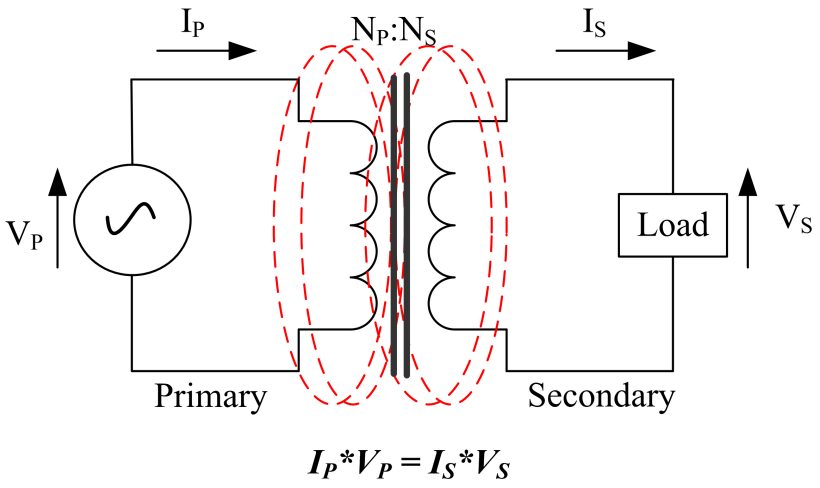

Figure 2.2: Equivalent circuit of an ideal transformer

Transformers can function as very efficient machines, but in the practice there are considerable amounts of energy losses. Modern power transformers have been designed to exceed 95 % efficiency, yet most of the power loss occure due to electrical resistance of the iron core and the windings (eddy-current losses). The lost energy dissipates in the form of heat. [Heathcote, 1998]. The equation 2.4 represents a transformer that functions at a real time efficiency [Heathcote, 1998].

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s} \tag{2.4}$$

where,

I_p primary current

I_s secondary current

Main parts of a transformer

A simplified schematic representation of a high voltage power transformer and its major technical components can be seen in the figure 2.3. A brief description of the components is shown in the following section.

- *Oil tank and its cooling system*: The oil tank is the outer part of a transformer, in which the core, windings and transformer oil are contained. Cooling collars are attached to the outer surface of the tank to achieve heat dissipation. For small transformers cooling is carried out through air circulation and heat radiation, however large transformers require adequate cooling system coolant substance. This is usually achieved

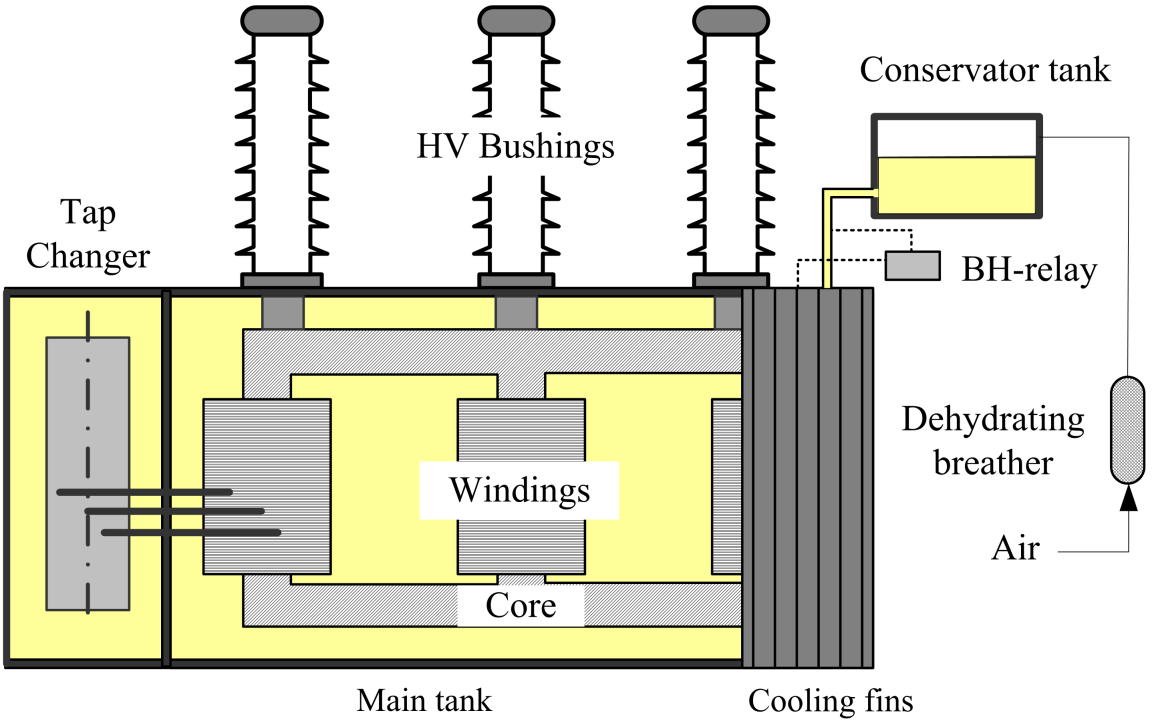

Figure 2.3: Schematic representation of a high voltage power transformer

by circulating transformer oil through the windings and and coolers [Heathcote, 1998].

- *The core*: It provides the main flux path for a magnetic field between primary and secondary windings. Generally the cores are constructed as hollow-core or shell-core of laminated steel layers insulated using varnish [Küchler, 2005].

- *Windings*: These are coils of high conductivity copper or aluminum wrapped around the limbs of a core. The primary winding is connected to input network and the secondary winding is connected to output network. For the power transformers operating at high voltages, layers of winding are insulated using oil-impregnated paper and blocks of pressboard [CEGB, 1982].

- *Tap changer*: Tap changers are external connections to the intermediate points along the primary and secondary windings, which allow the selection of a voltage ratio.

- *Bushing*: High voltage cables connecting a transformer to a network, are passed through bushing to insulate the cables from the main body of the transformer [Heathcote, 1998].

- *The conservator tank*: This tank is located on the top of the main tank and it is used to contain surge of transformer oil caused by thermal

expansion. The tank has a breather, which is a glass vessel filled with silica gel to protect the oil from moisture and to allow the gases in oil to diffuse in to the atmosphere. Due to this system transformer behaves as an open-breathing system that allows gas exchange between the main tank and the surrounding environment [Nynas Naphthenics, 2004].

- *The Buchholz relay*: Also known as a gas relay, is a safety device installed on the pipe connecting the main tank and the conservator. Under normal conditions the relay is completely filled with oil and it activates when the floats switch is displaced by certain accumulation of gas. This relay can switch off the transformer when a strong surge of oil flows to the conservator, or when the oil level falls down to dangerous levels [Nynas Napthenics, 2004].

- *Insulation materials*: It consists of cellulose paper wrappings around the windings and the transformer oil filling up the main tank. The general purpose of these materials is to insulate the different components of the transformer and to dissipate the heat produced due to thermal and electrical stresses.

2.2 Incipient faults in transformers

Incipient faults in transformers originate from a permanent and irreversible change in the transformer conditions. The incipient faults are very common in transformers and occur intermittently, causing accelerated aging and deterioration of the insulation system. Incipient faults can serve as warning of faulty conditions in transformer, however failure to notice the faults can lead to permanent failure of the transformer. Table 2.1 summarizes common incipient faults and failure modes occurring in power transformers.

Table 2.1: Most common modes of functional failures

System or component	Incipient fault	Failure Mode
Dielectric system: insulation materials	Arcing discharge, Partial discharges	Moisture, particles, contamination, aged insulation materials
Electromagnetic circuit: Core, windings	Localized hotspot, General overheating, Arcing or sparking discharges	short-circuited turn in winding conductor, circulating current

Partial discharge fault

A partial discharge is a highly localized electrical discharge of low intensity that occurs between two conductors placed apart [Danikas, 1993]. Partial discharges appear as short pulses that are often accompanied by emission of sound, light, heat and chemical reactions. The sources of partial discharges include voids and cracks in solid insulation, floating components such as water drops and air bubbles, and corona caused due to sharp edges of solid insulation, windings or tank. After initializing, a partial discharge can carry on with increasing intensity until terminating as an arc discharge. Usually this kind of fault is characterized by the generation of hydrogen and methane.

Arcing discharge faults

Sometimes a very high voltages can cause formation of plasma in oil through which electric current can flow freely as an arcing discharge [Arvidsson, 2005]. Arcing discharges generate very high temperatures (above 5000 °C) and large amount of gases, mainly acetylene and hydrogen. This type of faults are very dangerous and if not controlled, can cause excessive pressure in the transformer tank, causing even explosion.

Thermal faults (Hotspots)

Thermal faults arise as a consequence of overheating of conductors, short circuits, overheating of windings due to eddy currents, loose connections and insufficient cooling. Thermal faults can be classified as low temperature fault for temperature up to 150 °C, medium to high fault for temperature between 300 °C and 700 °C, and high temperature fault for temperature above 1000 °C. Localized thermal faults are known as hotspots. Temperature of a hotspot on metal surface can reach up to 1500 °C causing local heating of surrounding oil, leading to the generation hydrocarbon gases, mainly ethylene and methane.

The generation of fault gases is strongly dependent on the temperature, figure 2.4 represents the evolution of gases depending on the temperature. Consequently, hydrogen and methane are produced at around 150 °C, ethane at approximately 250 °C, then ethylene at approximately 350 °C and finally acetylene above 700 °C [Singh at al., 2010].

Characteristic gas generation due to faults

Depending on the type of fault specific patterns of gases (the gas compounds and their ranks in terms of concentrations) are generated in oil. The amount

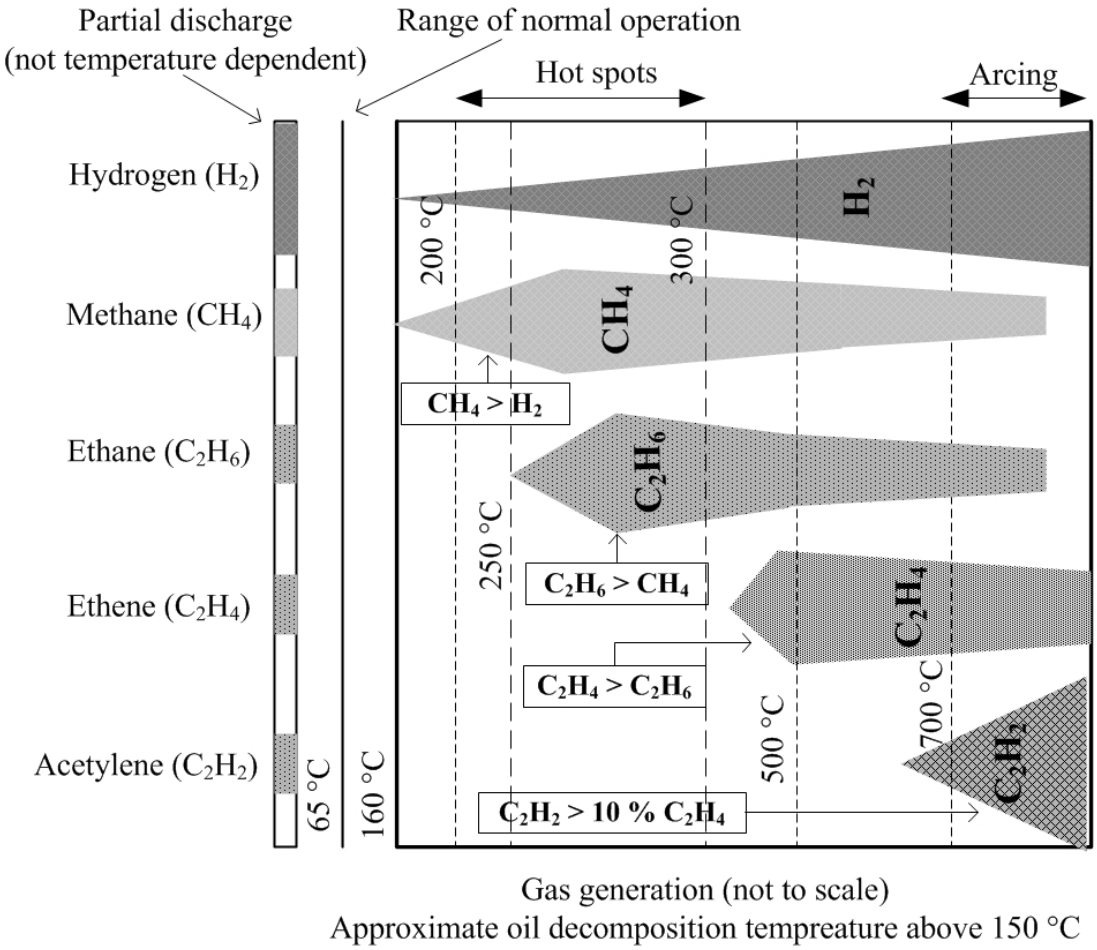

Figure 2.4: Temperature dependent evolution of gases in oil [Singh et al.,2010]

of gases generated in a specific pattern depends on the factors such as intensity and duration of the fault. Table 2.2 summarizes the typical gas concentrations for threshold and warning levels, which are based on the analysis of statistical data collected from service transformers filled with naphtenic oil [Arvidsson, 2001].

2.3 Dissolved gas analysis of transformer oils

The mineral oils are used in electrical equipments since 1891, mainly due to their ability to withstand electrical stresses [Heathcote, 1998]. The mineral oil properties such as, resistance to oxidation, aging stability, efficient heat transferability and high insulation capacity make them extremely useful as an insulation material in power transformers. Mineral oil acts as a vital fluid for transformers, it provides the dielectric medium to withstand high voltage, dissipate the heat generated in the core and windings, and impregnate the solid insulation. Besides, it functions as an information carrier that allow

Table 2.2: Characteristic gas formation

Case	Characteristic gas		**Threshold (ppm)**	**Warning (ppm)**
Normal ageing	H_2	Hydrogen	20	200
	CH_4	Methane	10	50
	CO	Carbon monoxide	300	1000
	CO_2	Carbon dioxide	500	20000
Oil overheating	CH_4	Methane	10	50
	C_2H_6	Ethane	10	50
	C_2H_4	Ethylene	20	200
Partial discharges	H_2	Hydrogen	20	200
Breakdown discharges	C_2H_2	Acetylene	1	3
Decomposition of cellulose	CO	Carbon monoxide	300	1000
	CO_2	Carbon dioxide	500	20000

to identify the internal condition of a transformer and required maintenance actions.

Transformer oil is a product obtained by distillation of crude oil at approximately 350 °C under atmospheric pressure. The crude oil is a complex mixture of hydrocarbon molecules and small amounts of sulphur and nitrogen compounds. The crude oils can be classified as heavy or light according to their main distillation residue, such as paraffinic, asphaltic or naphthenic residue [Heathcote, 1998]. The crude oil with naphthenic residue has been mainly preferred for manufacturing transformer oils.

The techniques of refining crude oil have a great impact on the required dielectric properties, oxidation stability and gas absorbing properties of a transformer oil (figure 2.5). Refining of crude oil consists of a several physical and chemical treatments that remove unstable aromatics, harmful polar molecules and ions.

Crude oil is firstly distilled at atmospheric pressure to remove components with low boiling points. Then the distillate is further refined under vacuum in order to generate fractioned distillates with different boiling points. After vacuum distillation, extraction techniques are applied to remove polar molecules, such as aromatics and polyaromatic molecules, as well as molecules containing sulfur, nitrogen and oxygen.

Since 1990 hydrogenation has been applied as a more efficient and environmental friendly extraction technique. Hydrogenation process converts polar compounds, aromatic and heteroatomic molecules into desired saturated

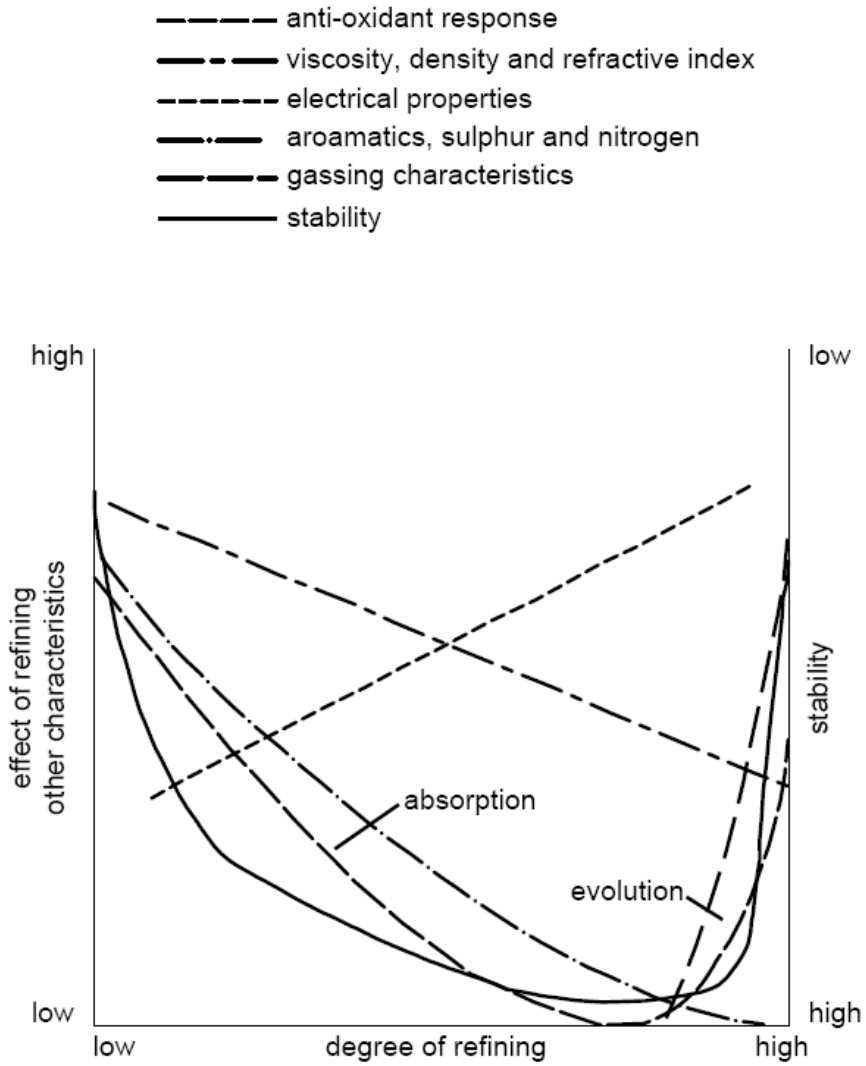

Figure 2.5: Effect of refining process on properties of oil [Heathcote, 1998]

ring and chain molecules through a controlled catalytic reaction using hydrogen under high pressure and temperature. The level of hydrogenation has significant impact on dielectric properties and thermal oxidation stability of the oil. Therefore, antioxidants or inhibitors are added to highly hydrogenated oils to enhance their resistance to thermal oxidation [Gradnik, 2007].

The transformer oil containing inhibitors is designated as inhibited oil. The inhibitors aim at retarding the oxidation mechanisms by means of stopping free radicals or peroxides, or by terminating chain reactions of peroxides. These compounds are included in the group of phenols, amines, aminophenols and sulfur. Thus, a transformer with inhibited oil can be operated at higher temperatures. Inhibited transformer oils are commonly used for air-breathing transformers in most of the Europe and America.

Lightly hydrogenated oils present certain amount of polar compounds containing sulfur, nitrogen and oxygen as natural antioxidants that provide sufficient oxidation stability. These type of oils are known as uninhibited oils [Gradnik, 2007].

Among the other additives in transformer oil are metal deactivators and passivators. Metal deactivators perform their function by decreasing the catalyst effect of metals. The passivators which are acid compounds that bind to metal surfaces by mean of the acid groups, forming a protective molecular layer that avoid the catalytic effect of metals in contact with the oil [Arvidsson, 2001].

Chemical composition

The basic chemical composition of transformer oils includes a mixture of different hydrocarbons structures, such as paraffinic, naphthenics, and aromatics (figure 2.6). The content of these hydrocarbons varies according to source of the crude oil and the refining process. Depending on the content of paraffinic structures (Cp), the oils can be classified as naphthenic ($Cp < 50$), intermediate ($50\% < Cp < 56\%$), and paraffinic ($Cp > 56\%$) [Nynas Naphthenics, 2004]. This classification is aimed at providing a guideline for the application of oil.

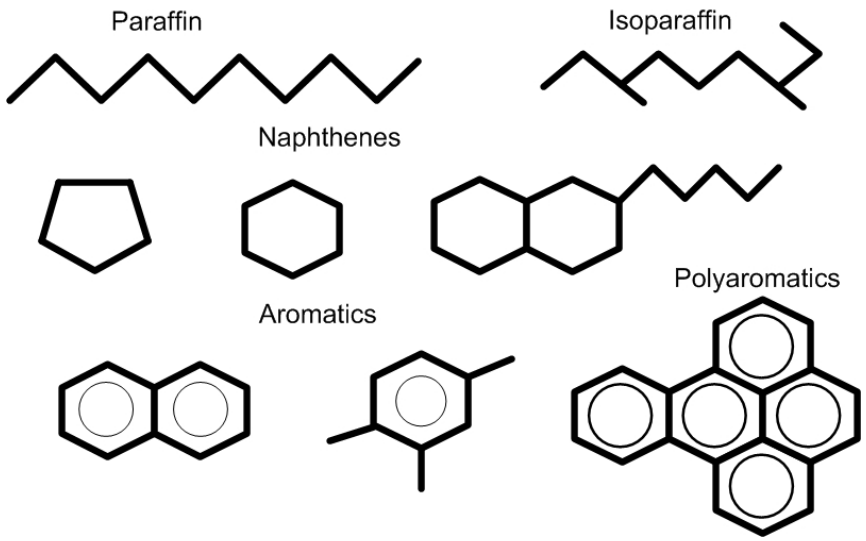

Figure 2.6: Basic structures of hydrocarbons in transformer oil [Nynas Naphthenics, 2004]

Paraffinic transformer oil offers low solvency for oxidation products and

moisture. They exhibit low thermal stability, when they are cooled below their pour point. Paraffin structures consist of saturated hydrocarbons forming straight type chains (N-alkanes) or branched type chains (isoparaffins). On the other hand, transformer oil with higher content of naphthenic molecules exhibit excellent properties at low temperature and high solvency for oxidation products and moisture. This type of oils are commonly preferred for application in transformers.

Naphthenic structures are known as cycloalkane compounds, which are saturated hydrocarbons made of one or more rings with 5 to 7 carbons attached with straight or branched type chains. In the case of aromatic structures, they are usually formed by one or several aromatic rings that can be combined with naphthenic and paraffinic structures. The aromatic molecules are commonly present in transformer oil as monoaromatic and polyaromatics (PACs), they provide excellent dielectric properties, good oxidation inhibition and high gas absorption [Nynas Naphtenics, 2004].

Additionally, transformer oil contains small percentage of aromatic structures bonded with elements such as nitrogen, sulfur and oxygen. Nitrogen compounds behave as inhibitors, passivators of copper and charge carriers. The nitrogen compounds in oil can be pyridines, quinones, carbanzoles and pyrolles. Sulfur content in oil varies with the properties of the crude oil and the refining process. Sulfur compounds exist in different forms, mainly as thiophens, carbazoles and sulphides. These compounds can act as oxidation inhibitors but also as an active initiator of copper corrosion.

The content of oxygen bonded to hydrocarbon in unused transformer oil is relatively small, but after oxidation it increases due to the production of certain acids, ketones, phenols, water and other oxygen containing molecules. Because of the strong polarity of these molecules they can influence the electrical field resulting in field losses. Additionally they can increase the rate of deterioration of paper insulation [Nynas Naphtenics, 2004].

Identification of oil components has a significant importance, yet a definitive standard chemical composition of oil has been impossible to establish. Figure 2.7 shows a hypothetical molecule of naphthenic transformer oil. A general chemical composition of the commercially available naphtenic transformer oils can be seen in table 2.3.

Properties of transformer oil

Transformer oils are manufactured to fulfill certain specifications to ensure efficient and reliable performance of a power transformer over longer ser-

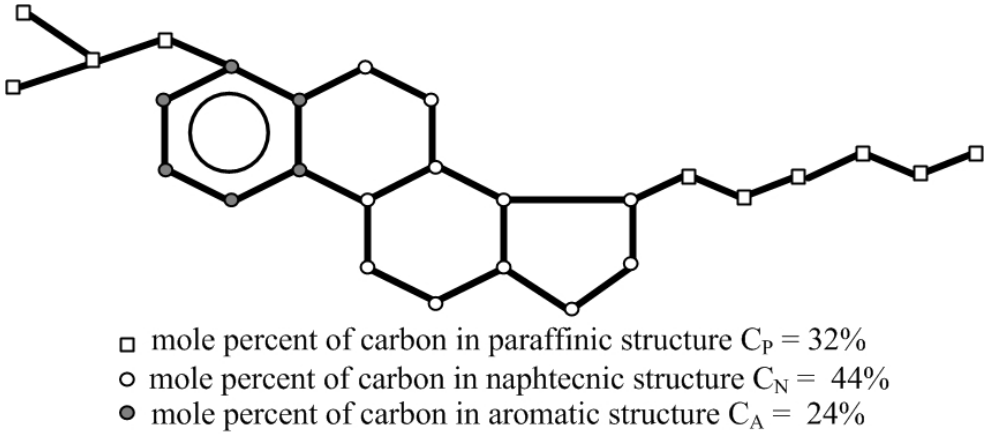

Figure 2.7: Typical oil molecule [Nynas Naphthenics, 2004]

Table 2.3: Chemical composition of a common transformer oil [Nynas Naphtenics, 2004]

Type	**Amount**
N-alkanes [wt %]	0.1- 2
C_P [%]	42 - 70
C_N [%]	28 - 50
C_A [%]	2 - 18
PAC [%]	0.02- 2.5
Sulphur [%]	0.01 - 1.0
Nitrogen [ppm]	1 - 300
Acid number [mg KOH/g]	0.01 - 0.03

vice span. These specifications are defined on the basis of the required physical, dielectric and chemical properties of the oil. Generally, a transformer oil should have following properties:

- high dielectric strength to withstand high voltage,
- low viscosity and low pour point for adequate heat exchange and flow circulation during operation at low temperature,
- high flash point to avoid risks of oil vaporization and thus risks of fire or explosions,
- sufficient resistance against oxidation and gassing under thermal and electrical stresses,
- ability to absorb gases and prevent formation of gas bubbles.

Oil with good oxidation stability can restrain the generation of decomposition products such as inorganic acids, alkali, corrosive sulfur, and sludge

under normal and faulty operations, which in consequence can protect the dielectric property of the oil and prolong the service span of the transformer.

General permissible limits/values pertaining to the specifications of transformer oils are provided by ASTM, ISO and IEC (Table 2.4). However, these values can vary depending on the particular requirements of an electric network and power transformer manufacturers.

Table 2.4: Specifications for naphthenic mineral oil for transformers

Property	**Unit**	**Typical values**	**Test methods**
Physical			
Apperance		Clear	IEC 60296
Density @20 °C	kg/dm^3	0.871	ISO 12185
Kinematic Viscosity	mm^2/s		ISO 3104
at 40 °C		9.4	
at -30 °C		900	
Pour point (max.)	°C	-60	ISO 3016
Flash Point (min)	°C	148	ISO 2719
Chemical			
Acidity	mg KOH/g	< 0.01	IECH 62021
Corrosive sulphur		non-corrosive	ASTM D1275B
Sulphur content	%	< 0.01	ISO 14596
Aromatic content	%	8	IEC 60590
Antioxidant, phenols	Wt %	0.38	IEC 60666
Water content	mg/kg	< 20	IEC 60814
Electrical			
Dielec. diss.n factor (DDF) @ 90 °C		< 0.001	IEC 60247
Interfacial tension	mN/m	50	ISO 6295
Breakdown voltage	kV	40-70	IEC 60156
Oxidation stability			
at 120 °C, 500 h			IEC 61125C
Total acidity	mg KOH/g	0.03	
Sludge	Wt%	< 0.02	

2.4 Oxidation of transformer oils

The oxidation of transformer oil is a complex process that involves free radicals in chain reactions [Sanghi, 2003]. Free radicals are electrically charged particles which require electrons from other molecules to achieve stabilization. They have one or more unpaired electrons which make them chemically very active to react with other molecules. Among the other properties of free radicals are their paramagnetism caused by unpaired electrons, electric neutrality, as well as their tendency to concentrate in a strong electric field. Due to the concentration in electric fields, the free radicals form collisions which produce more decay compounds [N'Cho et al., 2011].

In the air-breathing transformers the oxygen from atmosphere induce oxidation of the unstable hydrocarbon compounds in the transformer oil under normal operating conditions. The oxidation reactions are catalyzed by heat, moisture, copper and aluminum and further accelerated due to mechanical and electrical stresses [Nynas Naphthenics, 2004]. Over longer periods of operation the oxidation products, such as acids, aldehydes, ketones and other polar compounds accumulate in the transformer and promote further deterioration of the oil and formation of sludge [Nynas Naphthenics, 2004].

The schematic outline in figure 2.8 presents the oxidation process of a hydrocarbons. The oxidation process of hydrocarbons involves three basic stages: initiation, propagation and termination. In the initiation stage oxygen reacts spontaneously to breakdown a hydrogen molecule and form hydroperoxides, which again dissociate into free radicals [Sanghi, 2003]. The propagation is the rapid progression of the branched chain reactions, and the termination occurs with the formation of stable intermediate radicals and nonreactive compounds that donate hydrogen molecules to free radicals [Lipshtein et al., 1970].

The oxidation mechanism

The table 2.5 presents a simplified general model of possible reactions which occur during the oxidation of transformer oils [Nynas Naphthenics, 2004]. Reactions (1), (2) and (3) correspond to the initiation stage, in which peroxides and free radicals are produced under the influence of heat, high electrical stress and metals. From reactions (4) the propagation and branching takes place, resulting in the production of some stable and soluble byproducts, such as alcohols, aldehydes, carboxilic acids, ketones, ester and water [Arvidsson, 2001]. The hydrocarbon molecules follow the reaction path and lead to accumulation of the byproducts until the action of certain inhibitors form termination products suppressing further oxidation.

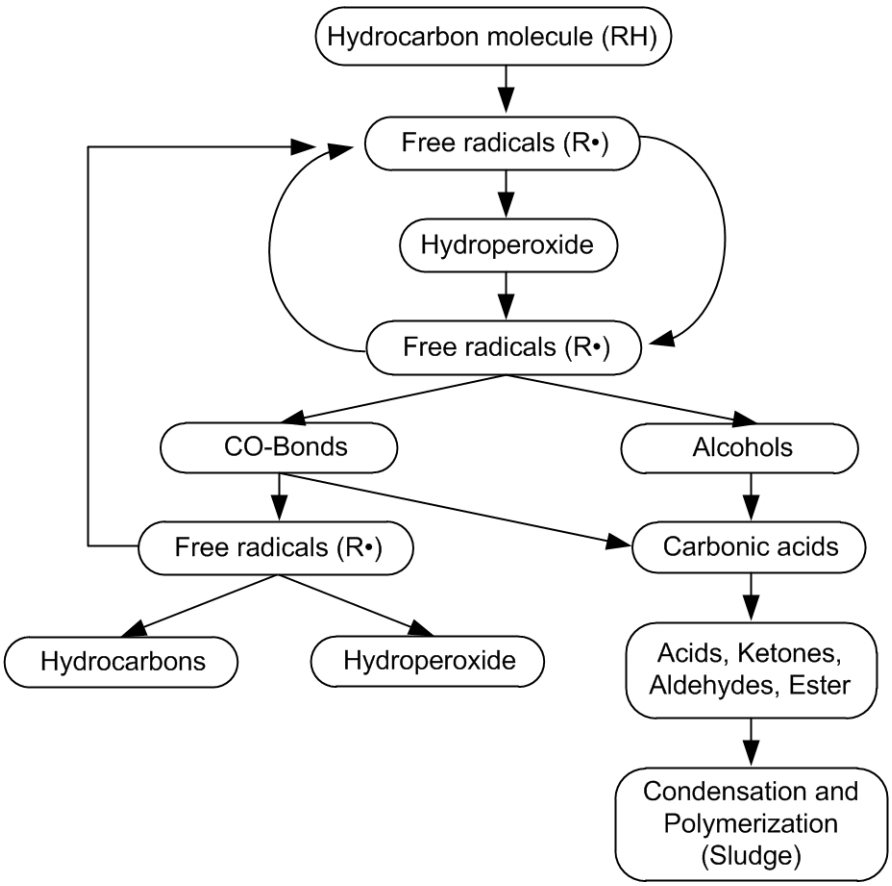

Figure 2.8: Oxidation process of a hydrocarbon

Table 2.5: Oxidation reactions [Nynas Naphthenics, 2004]

$RH \rightarrow R^{\bullet} + H^{\bullet}$	(1) Formation of free radicals
$R^{\bullet} + O_2 \rightarrow RO_2^{\bullet}$	(2) Formation of peroxy-radical
$RO_2^{\bullet} + RH \rightarrow RO_2H + R^{\bullet}$	(3) Formation of peroxide
$ROOH \rightarrow RO^{\bullet} + OH^{\bullet}$	(4) Decomposition of peroxide
$R^{\bullet} + R^{\bullet} \rightarrow R - R$	(5) Generation of hydrocarbon
$RO^{\bullet} + RH \rightarrow ROH + R^{\bullet}$	(6) Alcohol + Radical formation
$OH^{\bullet} + RH \rightarrow H_2O + R^{\bullet}$	(7) Water + Radical formation
$2ROH + O_2 \rightarrow 2RCHO + H_2O$	(8) Aldehyde formation
$2ROH + O_2 \rightarrow 2RCHO + H_2O$	(9) Ketone formation
$2RCOH + O_2 \rightarrow 2RCOOH$	(10) Carboxylic acid formation
$2RCOOH + ROH \rightarrow 2RCOOR + H_2O$	(11) Ester formation

In the case of complete decomposition, then colloidal suspensions made of insoluble compounds, with molecular weights between 450 to 550 Da, lead to the formation of waxes and dark sludge. The formation of waxes and dark sludge can impair the heat dissipation in transformer as well as can cause detrimental effects on the dielectric performance of the complete insulating

system [Sabau et al. 2000].

The Arrhenius law (equation 2.5) states that at higher temperatures the reaction rate increases due to the collisions between the molecules caused by higher activation energy [Arvidsson, 2001]. This equation can be used to represent the oxidation process of transformer oil undergoing a thermal decomposition of its hydrocarbon molecules due to a fault of certain intensity.

$$\frac{dC}{dt} = A_k \cdot e^{\frac{-\Delta E}{RT}} \tag{2.5}$$

where,

$\frac{dC}{dt}$ = change in concentration with the time $[mol/s]$

A_k = reaction constant according to kinetics [-]

ΔE = activation energy of the reaction $[J/mol]$

R = universal gas constant [8.314 $J/(K\Delta mol)$]

T = absolute temperature $[K]$

The thermal decomposition of hydrocarbons occurs as primary and secondary decomposition. The products of a primary decomposition are in equilibrium with their initial hydrocarbon, furthermore the products of primary decomposition decompose by heat as secondary decomposition products [Shirai et. al., 1997]. The thermal decomposition of an alkane is useful to represent the decomposition of new transformer oil due to carbon-to-carbon bonds splitting and dehydrogenation mechanisms. Usually carbon-carbon splitting decomposition of an alkane results into lower molecular weight alkane and alkene, in addition the alkane dehydrogentaion generates alkanes and hydrogen [Shirai et. al., 1997].

The primary decomposition of alkanes occurs at the normal operating temperature of transformers (below 160 °C) and the evolved products increments with an increase in the carbon number. The secondary thermal decomposition activates at higher temperatures (above 300 °C) in equilibrium with alkane and alkene molecules evolved from the primary decomposition as well as cycloalkanes and aromatic molecules of the transformer oil. Consequently, decomposition products comprise a gaseous mix of light hydrocarbons with less than 4 carbon number and hydrogen.

The equations 2.6 represent the thermal decomposition of an alkane into other alkane, alkenes and hydrogen. These reactions in equilibrium occurs simultaneously [Shirai et. al., 1997]:

$$\begin{aligned} &C_nH_{2n+2} \leftrightarrow H_2 + C_nH_{2n} \\ &C_nH_{2n+2} \leftrightarrow CH_4 + C_{(n-1)}H_{2(n-1)} \\ &... \\ &C_nH_{2n+2} \leftrightarrow C_{(n-2)}H_{(2n-2)} + C_2H_4 \end{aligned} \tag{2.6}$$

Therefore, the general chemical reaction is expressed as following [Shirai et. al., 1997]:

$$\begin{aligned} C_nH_{2n+2} \leftrightarrow A_0(H_2 + C_nH_{2n}) + A_1(CH_4 + C_{(n-1)}H_{2(n-1)} + .. \\ .. + A_n - 2(C_{(n-2)}H_{(2n-2)} + C_2H_4) \end{aligned} \tag{2.7}$$

Where, $A_0 + A_1 + ... + A_n - 2 = \Sigma A_i = 1(i = 0, 1, ..., n-2)$

Thus, the total mole number of products in the system is made of x moles of an alkane decomposed from 1 mole $(1-x)$ at certain temperature in equilibrium and the products $A_i x$ [Shirai et. al., 1997]:

$$(1-x) + 2\Sigma A_i x = (1+x) \tag{2.8}$$

The figure 2.9 shows some alkanes and their respective temperatures of decomposition.

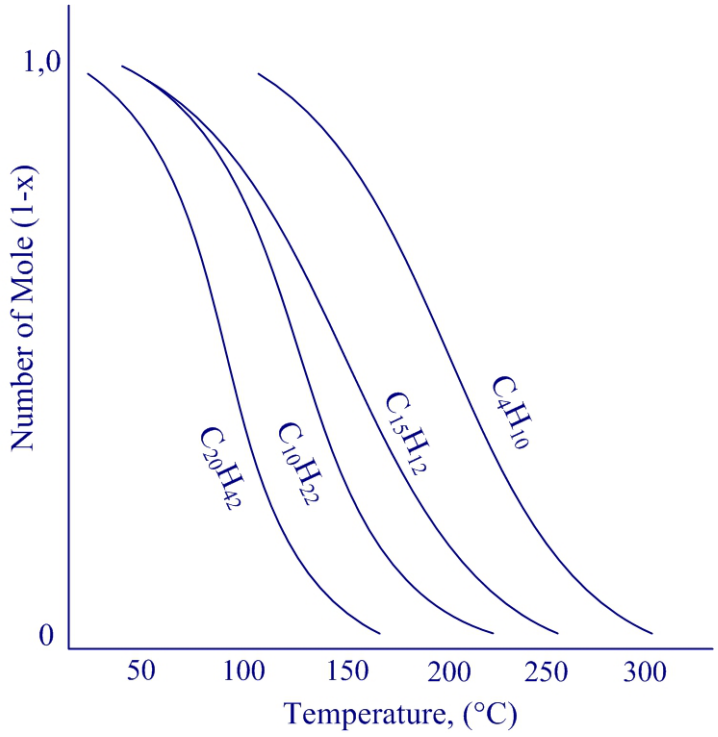

Figure 2.9: Decomposition of alkanes with respect to temperature[Shirai et. al., 1997]

The transformer oil has hydrocarbon molecules with an average carbon number of 20 and average molecular weight of approximately 280 Da. Thus, the thermal decomposition of eicosane ($C_{20}H_{42}$)aims at representing the process gas generation in transformer oil [Shirai et. al., 1997]. The thermal decomposition of eicoisane at above 300 °C can be defined by the following equation 2.9 [Shirai et. al., 1997].

$$\begin{aligned} C_{20}H_{42} \leftrightarrow\ & x_1CH_4 + x_2C_2H_6 + x_3C_2H_4 + x_4C_2H_2 \\ & + x_5C_3H_8 + x - 6C_3H_6 + x_7H_2 \ldots. (at \quad 300\ ^\circ\text{C}) \end{aligned} \tag{2.9}$$

with,
$x_1 + 2(x_2 + x_2 + x_4) + 3(x_5 + x_6) = 20$
$4x_1 + 6x_2 + 4x_3 = 2x_4 + 8x_5 + 6x_6 + 2x_7 = 42$

Gassing and stray gassing behavior of oil

The gassing of transformer oil means formation of hydrocarbon gases in oil, it is associated with aging of the insulation system. The gassing of oil is accelerated due the impact of electrical, thermal, mechanical and chemical stresses. The main factors influencing the gassing process in the oil are presented in figure 2.10.

Additionally, certain types of oils exhibit an abnormal gassing behavior under normal operating temperatures, independent of aging of insulation or faults in the transformer. This effect has been distinguished as 'stray gassing' by the International Council on Large Electric Systems (in French: Conseil international des grands réseaux électriques) CIGRE [Duval, 2004]. The stray gassing is characterized by a rapid gassing behavior that generates predominately high concentrations of hydrogen and methane. This increasing tendency remain until the concentrations reached a plateau.

This gassing mechanism has not been identified completely, nevertheless it seems to be caused by strong hydrogenation during oil refining. Stray gassing of oil is highly influenced by other transformer materials which trigger catalytic reactions between oil and metal surfaces such as copper, grain-oriented steel, zinc-plated steel and varnishes [Höhlein, 2006].

Breakdown of oil due to electrical stress

Breakdown of mineral transformer oil due to electrical stress is caused by certain electro-thermal mechanisms which are being investigated over the last decades and yet not fully understood. Besides, the complex chemical composition of transformer oil exhibits an inconsistent behavior that makes

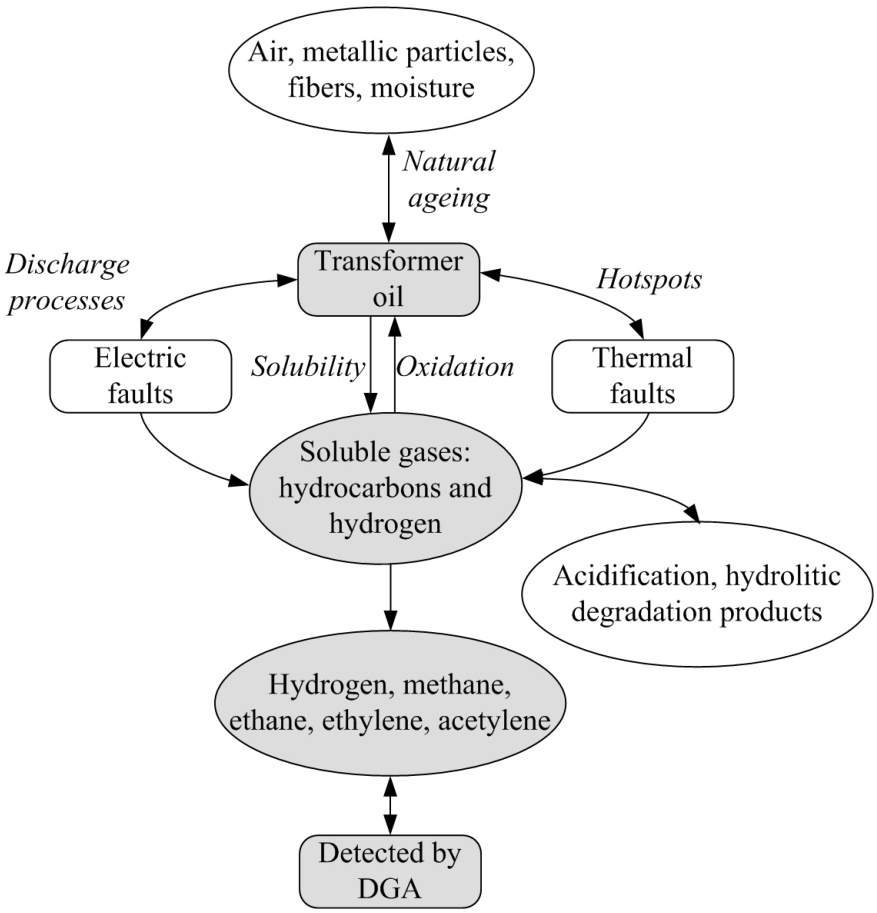

Figure 2.10: Factors influencing the gassing process of oil

it difficult to predict the mechanisms of oxidation reactions.

The breakdown of transformer oil due to electrical stress has been explained by the theory of avalanche ionization of atoms dissociated by electron collisions [Wadhwa, 2012]. Figure 2.11 represents the simplified theory of oil breakdown based on avalanche ionization of atoms. During discharge events electrons are introduced in the oil by the cathode, creating an electro-thermal condition that produces localized high temperatures. In this condition small gas bubbles are generated as charge carriers which propagate further ionization in oil, that in turn cause further generation of fault gases. This theory applies to pure transformer oil free from any particles and moisture.

Enthalpies of gas generation in oil

The decomposition products are kinetically determined by the energy produced by the fault. Lately Jakob, Noble and Durkam [Jakob et al. 2012] presented an approach based on the enthalpies of formation of fault gases and average energies required for breaking and formation of bonds during

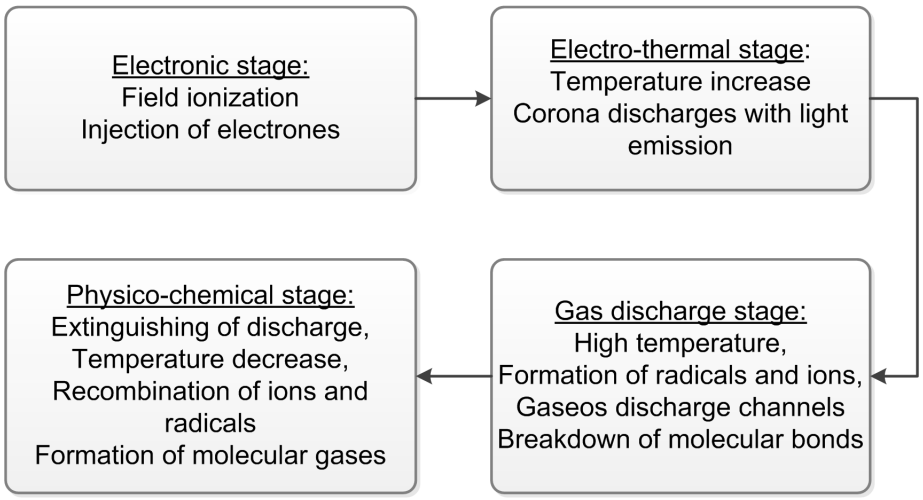

Figure 2.11: Development of electrical breakdown of oil during fault gas generation [Schmidt, 1982]

decomposition of n-octane (C_8H_{18}). Table 2.6 presents the relative enthalpies required for the fault gas formation.

Table 2.6: Bond dissociation enthalpy [Klotz et al., 1986]

Gas compound	CH_4	C_2H_6	C_2H_4	H_2	C_2H_2
Relative enthalpies (kJ/mol)	77.1	93.5	104.1	128.3	278.3

Thus, the generation of methane, ethylene and ethylene requires the least generation energy, while hydrogen and acetylene need much larger generation energy. Therefore, generation of acetylene in large amount is indication of a severe fault, such as arcing discharge which can result in serious damage to a transformer. Also hydrogen, which is generated in different amounts by almost all faults, provides certain indication of type and intensity of the related fault.

The antioxidants or inhibitors

Oxidation should be controlled or slowed down in order protect the dielectric properties of the oil. For that reason inhibitors are incorporated into the oil formulation to interrupt the propagation of free radical chain reactions and to terminate the oxidation process. Equation 2.10 represents the action of an oxidation inhibitor [Sanghi, 2003].

The incorporation of an inhibitor (AH) will provide a labile hydrogen atom that can compete with the hydrocarbon and produce an inactive free radical (A), terminating the chain reactions. Inhibitors or antioxidants are usually phenolic or aromatic amine compounds, among the most common inhibitors are 2.6-ditertiarybutylphenol (DBP) and 2.6-ditertiarybutyl-4-methyl phenol (DBPC) [Sanghi, 2003].

$$\begin{aligned} &R^{\bullet} + AH \leftrightarrow R - H + A^{\bullet} \\ &RO^{\bullet} + AH \leftrightarrow R - O - H + A^{\bullet} \\ &R - O - O^{\bullet} + AH \leftrightarrow R - O - OH + A^{\bullet} \\ &OH^{\bullet} + AH \leftrightarrow H_2O + A^{\bullet} \end{aligned} \tag{2.10}$$

Though conventionally refined transformer oils contain natural antioxidant compounds, the incorporation of inhibitors is essential to retard the rate of oxidation and prolong the service life of the oil. However, the inhibitors can deplete with the ongoing oxidation reactions, leading to higher rates of oxidation. Therefore adequate monitoring of the inhibitor content should be maintained.

2.5 The gas-in-oil as ideal solution

A solution made of oil and the gases dissolved in it can be assumed as an ideal solution if its thermodynamic properties are similar to those of an ideal gas mixtures. Ideal solutions are characterized by equivalent interactions among molecules of the same type of chemical structure. Furthermore, in these solutions the enthalpy of mixing is zero and the entropy of mixing is defined by change in the molar Gibbs free energy as shown in the equation 2.11.

$$\Delta G_{m,mix} = RT \sum_i x_i \ln x_i \tag{2.11}$$

where,

$\Delta G_{m,mix}$ = change in Gibbs free energy per mole of solution, kJ

x_i = mole fraction of component 'i'

The molar Gibbs free energy expression can be written in terms of chemical potentials, as following [Atkins et al., 2006]:

$$\Delta G_{m,mix} = \sum_i x_i \Delta \mu_{i,mix} \tag{2.12}$$

with,
$\Delta\mu_{i,mix} = RT \ln x_i$; which is defined as change in the chemical potential of component 'i' on mixing.

The chemical potential of a component 'i'in an ideal solution can be expressed as [Atkins et al., 2006] :

$$\mu_i = \mu_i^* + \Delta\mu_{i,mix} = \mu_i^* + RT \ln x_i \tag{2.13}$$

Where, μ_i^* is chemical potential of pure liquid 'i'

When there is an equilibrium between liquid and gas phases, then the chemical potentials of 'i' are equivalent ($\mu_{i,liq} = \mu_{i,gas}$) [Atkins et al., 2006].

Hence, for a given component 'i' the Raoult's law can be applied over the whole range of concentrations as following [Atkins et al., 2006]:

$$P_i = x_i * P_i^* \tag{2.14}$$

where,

P_i = vapor pressure of a component i

x_i = mole fraction

P_i^* = vapor pressure in pure state

The Raoult's law in a multicomponent ideal solution can be written as:

$$P = P_a^* x_a + P_b^* x_b + ... \tag{2.15}$$

Solubility of gases in oil

The ability of fault gases to dissolve in oil is highly dependent on the factors such as temperature, pressure as well as chemical composition. Figure 2.12 represents the solubility of hydrocarbon gases in oil as a function of temperature. The solubility of hydrocarbon gases in oil is higher than the solubility of hydrogen and atmospheric gases in oil. Furthermore, the solubility of hydrogen, nitrogen, carbon monoxide and oxygen increases with increase in temperature, while the solubility of carbon dioxide, acetylene, ethylene and ethane reduces with the increase in temperature [Griffin, 1988].

One of the most common methods applied for quantification of gas solubility in oil is the Henry's law. The principle of this law is limited to dilute ideal

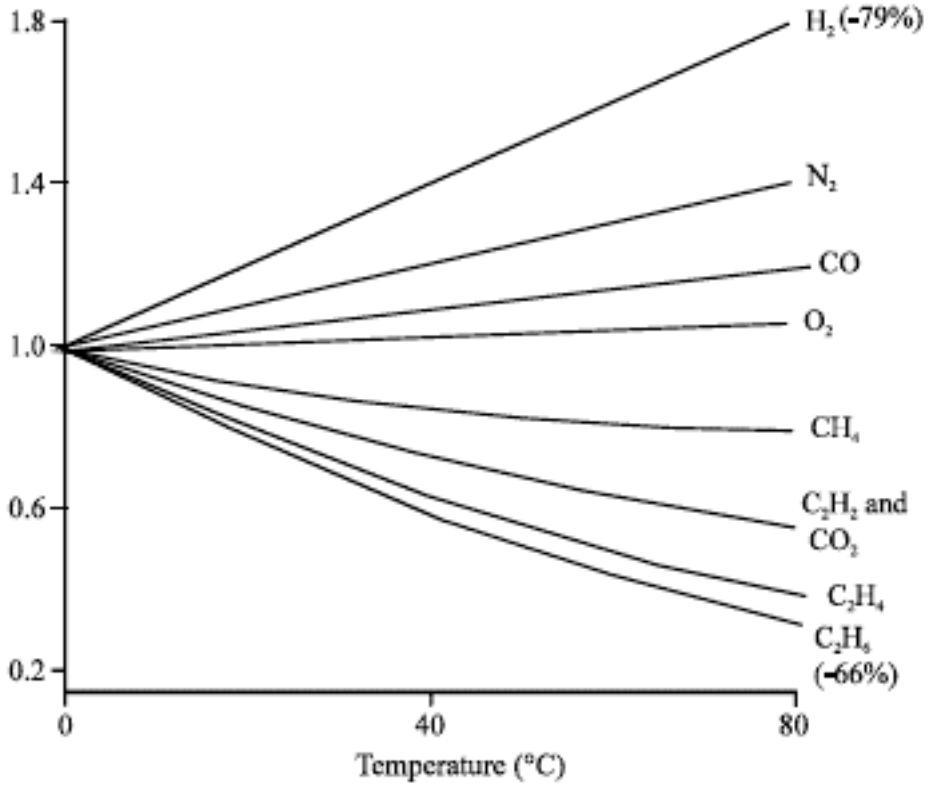

Figure 2.12: Temperature dependent solubility of gases in oil [Griffin, 1988]

solutions, similar to the gas-in-oil solution in transformer. The Henry's law states that the concentration of a gas dissolved in a liquid is directly proportional to the partial pressure of that gas in equilibrium with the liquid at a constant temperature [Atkins et al, 2006]:

$$P_{gas} = k_H C \tag{2.16}$$

Where,

P_{gas} = partial pressure $[atm]$

k_H = temperature-dependent Henry's constant $[atm/mol]$

C = concentration of the dissolved gas in the liquid $[mol/l]$

The Bunsen solubility coefficient, α, is defined as the volume of gas that can be absorbed by the unit volume of solvent at a specified temperature, under the partial pressure of the gas of 101.3 kPa [Fogg et al., 1991]. For ideal solutions the equation is written as equation 2.17 [Battino et al., 1966].

$$\alpha = \frac{V_{gas}}{V_{sol}} \cdot \frac{273.15}{T} \tag{2.17}$$

Where,

V_{gas} = volume of dissolved/absorbed gas, [l]

V_{sol} = volume of absorbing solvent, [l]

T = absolute temperature, [K]

Another way to determine solubility of gases in oil is by means of the Ostwald coefficient, L, which is defined as the ratio of dissolved gas volume (V_{gas}) to the solvent volume (V_{sol}) at the experimental temperature and pressure conditions (equation 2.18) [Battino et al., 1966].

$$L = \frac{V_{gas}}{V_{sol}} = \frac{C_{liq}}{C_{gas}} \tag{2.18}$$

where,

V_{liq} = volume of the gas in the liquid phase [l]

V_{gas} = volume of the gas in the gas phase [l]

C_{liq} = concentration of the gas in the liquid phase [mol/l]

C_{gas} = concentration of the gas in the gas phase [mol/l]

The Ostwald coefficient is an equilibrium constant independent of the partial pressure in ideal solutions, additionally it can be applied to determine the concentration of gas in one phase when the concentration of gas in the other phase is known [Griffin, 1988]. The table 2.7 presents Ostwald coefficient estimated for gases dissolved in a transformer oil with density of 0.880, at 25°C and 1 atm [Griffin, 1988].

Table 2.7: Ostwald coefficients [Griffin, 1968]

Gas	**Ostwald coefficient,** L
O_2	0.138
N_2	0.0745
CO_2	0.9
CO	0.102
H_2	0.0429
CH_4	0.337
C_2H_6	1.99
C_2H_4	1.35
C_2H_2	0.938

In general, solubility coefficients are estimated experimentally or based on certain empirical methods. The American Society for Testing and Materials has proposed methods (ASTM norms D2779 and D2780) to determine the solubility of gases by means of Ostwald coefficients obtained from empirical equations and oil standards of known solubility parameters [Griffin, 1968].

2.6 Diffusion of gases

In the case of air-breathing transformers with open conservator, there is a continuous exchange of gases between the transformer oil and the surrounding atmosphere, which is referred as breathing of transformers. The conservator allows a free gas exchange at the oil-air interface, thus dissolved gases can diffuse-out continuously while oxygen and nitrogen from the atmosphere keep the oil saturated.

Diffusion process is a part of mass transport phenomena, and denotes the mixing of two or more substances or the movement of a fluid from an area of higher concentration to an area of lower concentration [Benner et al., 1982]. Diffusion process exhibit two important characteristics: its random nature, and the mass transport until reaching an equilibrium. Diffusion is often complimented by convection, which makes it difficult to investigate as a separate process.

Diffusion can be described by the Fick's laws, which is aimed at representing the mass transport due to diffusion and the rate of change of concentration in space. The first Fick's law (equation 2.19) is used for steady-state condition, when the concentration within the diffusion volume does not change with the time [Benner et al., 1982].

$$J = -D \cdot \frac{\partial C}{\partial x} \tag{2.19}$$

where,

J = diffusion flux [$mol/m^2 s$]

D = diffusion coefficient [m^2/s]

C = concentration of diffusing gas (ideal mixtures) [mol/m^3]

x = position in the diffusion volume [m]

The second Fick's law (equation 2.20) is used in non-steady condition and time dependent diffusion. It relates the rate of change of concentration at

certain location to the spatial variation of the concentration at that location [Scott et al., 2002].

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2} \tag{2.20}$$

Where, t is time in seconds.

A one-dimensional solution of equation 2.20 was obtained to represent the diffusion of an instantaneous point-source injection of mass M in an area $A = a^2$ at $x = 0$ and $t = 0$, see figure 2.13.

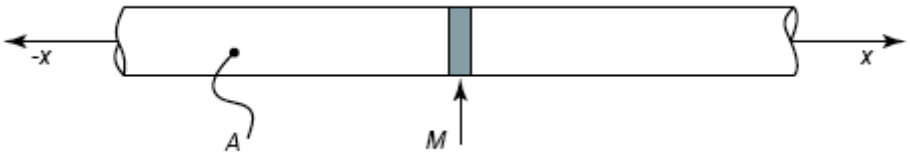

Figure 2.13: One dimensional diffusion tube

Thus the injected mass of concentration $C(x,t)$ is given by the following expression [Scott et al., 2002].

$$C(x,t) = \int_v C(x,t)\partial V \tag{2.21}$$

Based on the following boundary conditions, the solution of the integral of concentration within a diffusion volume can be solved as shown in equation 2.22.

- At $t = 0$ all amount of solute is concentrate at $x = 0$.
- The concentration is finite within the diffusing volume.
- The total amount of solute is constant at all times.

$$C(x,t) = \frac{M}{A\sqrt{4\pi Dt}} e^{-x^2/4Dt} \tag{2.22}$$

In the case of a pure diffusion process, the instantaneous point source diffusion model could be applied to estimate diffusion coefficient of compounds within a certain volume. For instance, diffusion of gases dissolved in the oil volume of a transformer tank, however gases generated in transformers are

mainly subjected to many concurrent processes that prevent estimations of pure diffusion coefficients of gases dissolved in the oil volume.

The mass transfer velocity of a gas diffusing through an interface between oil and air can be described by the mass transfer coefficient [Acheson, 1990]. The driving forces behind the mass transfer process are concentration gradient and diffusion of molecules through a steady interface layer of certain thickness δ, thus the concentration gradient can be expressed by equation 2.23 [Guo at al., 2003].

$$\frac{J}{A} = -(\frac{D}{\delta})\frac{\partial c}{\partial x} \tag{2.23}$$

Since the diffusion cannot be measured through the interface layer, the mass transfer coefficient (K_{liq}) replaces the expression D/δ in equation 2.23 [Guo et al, 2003].

$$\frac{dW_{liq}}{dt} = -AK_{liq}\left(C_{liq} - \frac{C_{gas}}{H}\right) \tag{2.24}$$

$$K_{liq} = c_H K_{gas} \tag{2.25}$$

where,

$\frac{dW_{liq}}{dt}$ = gradient of amount of dissolved gas [$\mu g/h$]

A = surface area of diffusion [m^2]

K_{liq} = liquid phase mass transfer coefficient [m/h]

K_{gas} = liquid phase mass transfer coefficient [m/h]

C_{liq} = concentration of gas in liquid phase [$\mu g/m^3$]

C_{gas} = concentration of gas in air [$\mu g/m^3$]

c_H = Henry's dimensionless constant [-]

2.7 The dissolved gas analysis methods

Dissolved gas analysis (DGA) is among the most widely used method for detection and diagnosis of faults in the transformers. The conduction of DGA consists of oil sampling, analysis of gas-in-oil concentrations and fault diagnostic based on the obtained concentrations using certain interpretation schemes. A proper implementation of each step of the DGA method ensures a reliable identification of faults in a transformer and indicate the timings of

maintenance and repair to prevent its failure [Sun et al., 2012].

The DGA for a transformer is usually implemented only at certain maintenance intervals, however latest state-of-the-art techniques can carry out continuous DGA monitoring though an online system and give early warnings about any sudden increase of fault gas concentrations.

Precise interpretations of DGA results requires sufficient knowledge of relationship between gas concentrations/patterns and type of faults as well as their severity. The interpretation schemes usually consist of thresholds, ratios and graphical representations of concentrations of key gases pertaining to different types of faults. The most common interpretation schemes for fault diagnostic include the key gas analysis, Dornenberg and Rogers Ratio, Nomograph, IEC ratio, Duval Triangle, and CIGRE interpretation scheme [Sun et al., 2012]. These interpretations schemes show certain limitations which can lead to uncertain fault diagnostic, therefore it is recommended to use more than one scheme for a fault diagnostic.

Among interpretation schemes, the most popular and frequently used scheme is the key gas method, which consist of correlating a fault type with the concentration of one of the key gases ($C_2H_4, CO, H_2 \ or \ C_2H_2$), for instance high concentrations of hydrogen predicts partial discharge, ethylene indicates overheating above 500 °C and acetylene is characteristic for a thermal fault above 1000 °C. The key ratios consist of CH_4/H_2 for partial discharge, C_2H_2/C_2H_4 for arcing discharge, C_2H_2/C_2H_6 for discharges, and C_2H_4/C_2H_6 for hotspots. These ratios of gas concentrations are compared with certain threshold values corresponding to the types of faults [Sun et al., 2010].

Another method, here referred as gas generation pattern method, is a graphical method which is based on the assumption that the patterns of concentration ratios of fault gases generated due to certain type of faults are always identical. The method consists of plotting normalized concentrations of key fault gases in the following sequence; H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and comparing the obtained pattern to the typical fault gas generation patterns presented in the figure 2.14. The concentrations of the key gases are normalized by the concentration of the dominant gas concentration (with maximum concentration) among the key gases; therefore the normalized concentration of the dominant gas is always 1.0 [-]. This method has proven its potential for fault diagnostics in transformer using DGA [Okubo et al, 1999 and Tshukioka et al, 1978].

The interpretation scheme proposed by CIGRE TF 15.01.01 [Mollmann et al., 1999] is one of the most recent DGA interpretation scheme (table 2.8).

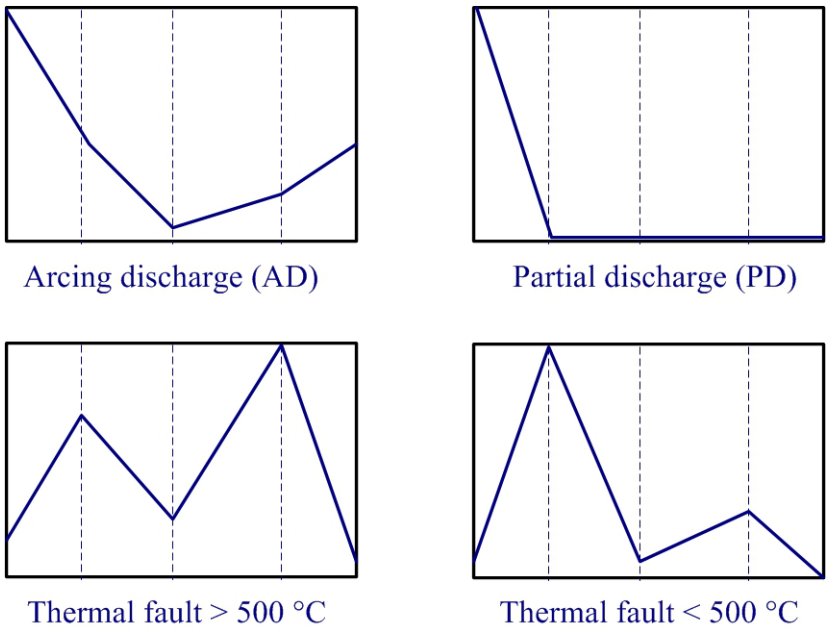

Figure 2.14: Gas generation pattern method

Table 2.8: Fault diagnostic by applying the CIGRE fault interpretation scheme (partial discharge)

Part I: Key gas ratios		
Key gas	**Ratio [-]**	**Fault type**
(C_2H_2/C_2H_6)	> 1	Arcing discharge (AD)
(H_2/CH_4)	> 10	Partial discharge (PD)
(C_2H_4/C_2H_6)	> 1	Oil overheating (OH)
Part II: Thresholds [ppm]		
Key gas	**Thrsh. [ppm]**	**Fault type**
C_2H_2	> 20	Arcing discharge (AD)
H_2	> 100	Partial discharge (PD)
$\sum C_xH_y$	> 1000	Oil overheating (OH)
$\sum CO_x$	> 10000	Cellulose degradation (C)

The CIGRE interpretation scheme is aimed at addressing certain discrepancies in the other interpretation schemes by incorporating up to date scientific knowledge and practical experiences. The method is based on key gas concentrations and ratios, which are compared with the thresholds established for a sound operation of a transformer. The CIGRE scheme allows diagnostics of several faults that could be occurring simultaneously, and in some cases it can identify the fault location. However, this scheme as well as the other interpretation schemes cannot provide a reliable diagnostic of instantaneous faults such as partial discharge [Sun et al., 2010].

During this study the data obtained from experimentally simulated faults and the analysis of corresponding fault gas generation is used to evaluate the accuracy and reliability of the CIGRE interpretation scheme and the gas generation pattern method.

Quality control of transformer oil

Transformer oil requires to fulfill certain quality criterion to ensure its suitability as dielectric insulation in the power transformers. The international standard norm proposed by International Electro-technical Commission (IEC 60422) includes the criterion used for evaluation of the insulation quality of transformer oil and cellulose paper [Nynas Naphtenics, 2004]. The table 2.9 present the criterion for condition assessment of insulation oil. These criterion provide a basis for better DGA diagnostic of a given fault condition in transformers.

Table 2.9: Criterion for condition assessment of an insulation oil

Test	**Limit value**	**Interpretation and possible action**
Total acid number [mg/g]	< 0.02 > 0.15	normal condition heavy oxidation, oil change or regeneration necessary
Water content [ppm]	< 15 > 25	normal condition cellulose aging, remove water by degassing
Corrosive Sulfer [ppm]	< 0.1 > 3.5	normal condition very high
Breakdown Voltage [kV] $>$170 kV transformer	< 50 > 50	moisture, sludge, particles normal condition
Power factor [%], tan at 90 °C	> 5	contaimination from metal, organics. Regeneration or change of oil
Peroxide number	< 1 > 5 > 10	normal condition, slow aging rapid aging rapid aging and hotspots
Interfacial tension		polar compounds from aging or contamination
Visual appearance	clear turbid	normal condition aging, particles

3 Experimental Setups and Measurement Equipments

The design and construction of several experimental setups were required to investigate the gassing behavior of the transformer oils. These setups were aimed at simulating the gas-in-oil generation as it occurs in power transformers operating with certain thermal or electrical faults.

This chapter provides a detailed description of the experimental setups and the equipments used for these investigations. Furthermore, the technical descriptions of the state of art DGA equipments are also presented in the chapter.

3.1 Small scale setup

This setup was constructed to facilitate the experiments related to the generation of gases in transformer oil as a consequence of partial discharges or hotspots. The main parts of the setup are described as following.

3.1.1 Oil tank (12 liter) and high voltage supply system

The figure 3.1 shows a schematic representation of oil tank and the high voltage supply system. The oil tank of 12 liter capacity was made of a plexiglass cylinder and sealed at the top and bottom using steel plates. A smaller tank of 6 liter capacity was placed on the top of the oil tank to simulate the function of open-breathing conservator tank to contain the oil in case of thermal expansion.

The setup consisted of a high voltage transformer (30 kV), an autotransformer (0-230 V AC), a voltage controlling panel and a security cabinet with warning lights.

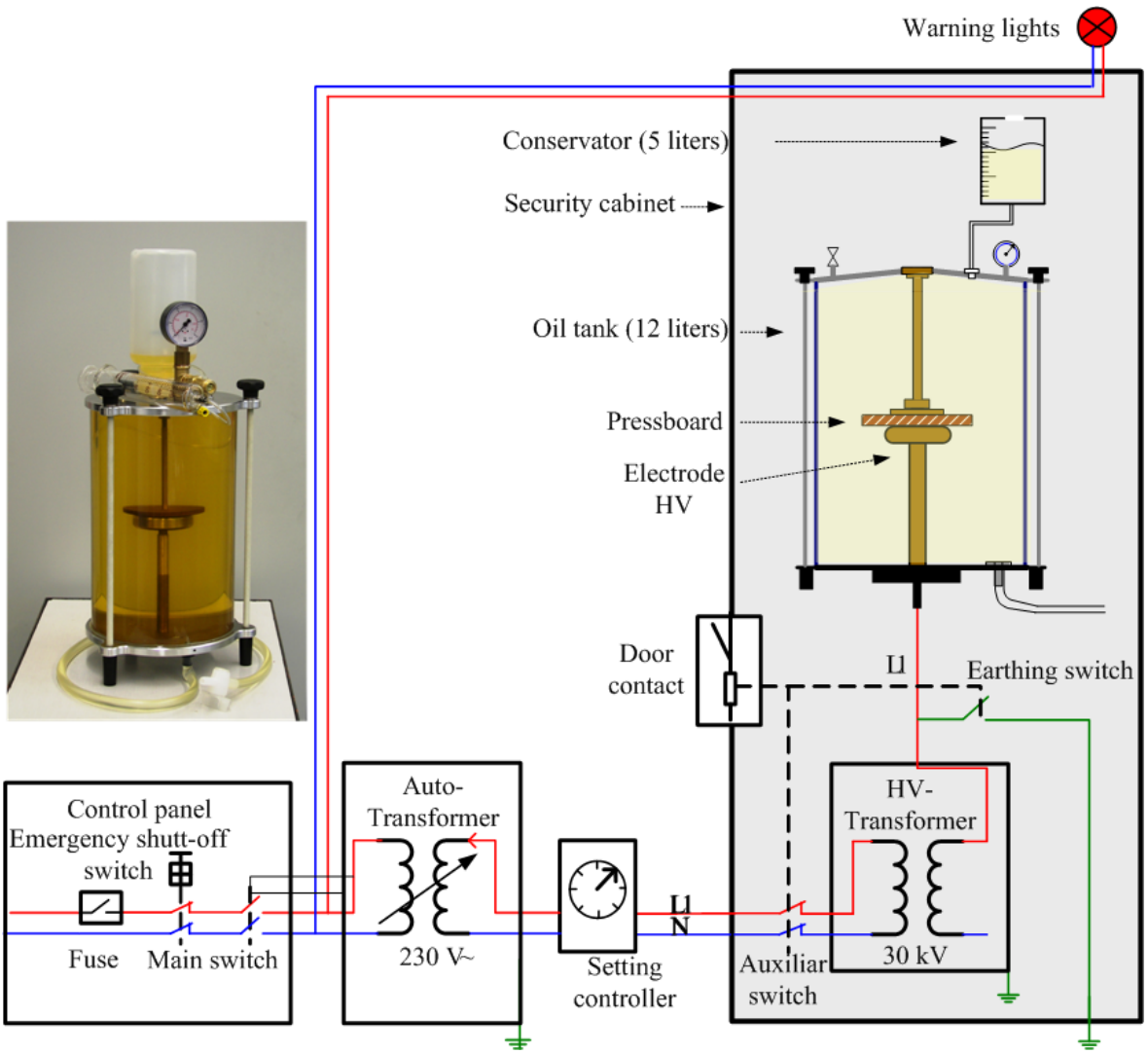

Figure 3.1: High voltage suppply circuit for partial discharges in the oil tank (12 liters)

3.1.2 Partial discharge (PD) system

The electrodes used to generate partial discharge consisted of a rod, a brass disk, and a pressboard. The disk was placed between the rod and the pressboard. Several disks of different diameters, thickness, surface and edge geometry were tested in the setup in order to achieve a stable partial discharge event. As a consequence, a square and rough edged disk of 1.5 mm thickness and 25 mm diameter was selected for the following partial discharge experiments. The pressboards of 8 cm x 8 cm size and approximately 2 mm thickness were treated before their utilization in order to remove air and moisture trapped into the material. Figure 3.2 shows a schematic representation of the disk electrodes.

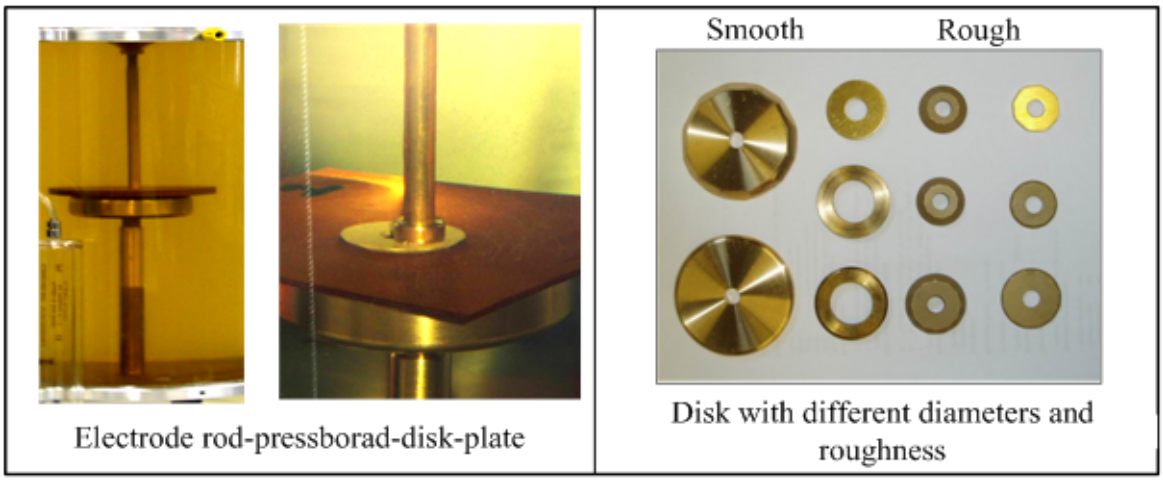

Figure 3.2: Disk electrode arrangement

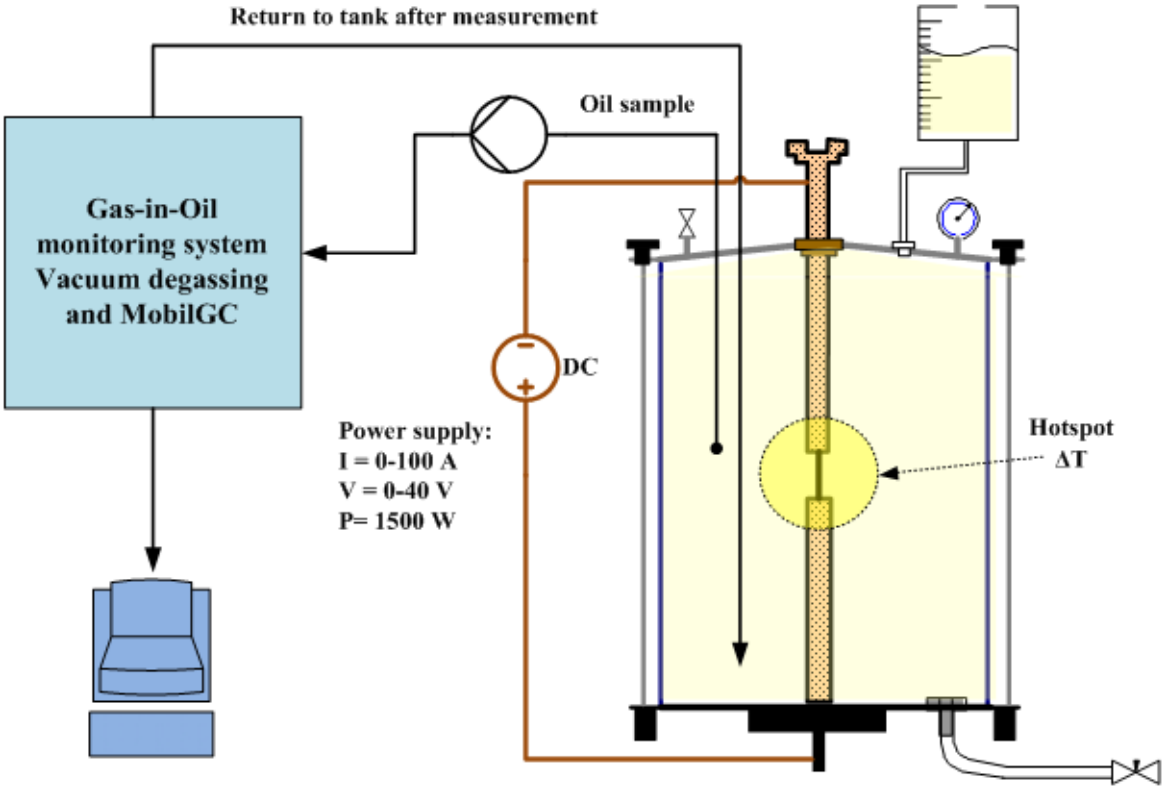

Figure 3.3: Hotspot setup for gas-in-oil analysis

3.1.3 Hotspot system

The figure 3.3 presents a diagram of the experimental setup for hotspots. For the hotspot experiments was used the same tank setup as for the partial discharge experiments (see Section 3.1.1), with exception of the disk electrodes and the high voltage circuit. Instead, two rods supporting a piece of semi-conductor material (graphite lead) were inserted through the top and

the bottom covers of the oil tank. Due to high resistance the semi-conductor materials like graphite induce high temperature in short time when they are subjected to electric current. This allows to create hotspot in the oil tank to simulate thermal faults in the transformer. Apart from the graphite other materials were tested to create hotspots, nevertheless only graphite induced the temperatures high enough to trigger oxidation of the transformer oil.

3.2 Large scale setup system

This setup was constructed with the purpose to carry out investigations on the effect of electric stress at high voltage (approximately 100 kV) on the gassing behavior of the transformer oils. This system was designed to resemble the main concept of oil insulation in a power transformer with a main tank, an air-breathing conservator and an oil circulation system. The following section presents a technical description of the main parts of the setup.

3.2.1 Oil tank (600 liter) and high voltage system

The figure 3.4 displays a simplified representation of the oil tank and its high voltage circuit. The main oil tank of 600 liter capacity was made of a fiber glass cylinder covered with copper layers. The top and the bottom of the tank were sealed using steel plates covers. A high voltage bushing was fixed on the top cover to provide connections to the high voltage circuit. Several sensors were inserted through the top cover to measure temperature, pressure and oil level at different locations in the tank.

An additional tank of approximately 60 liters capacity was placed above the oil tank which performed the function of an open-breathing conservator where the oil is in contact with air at ambient conditions. Both of these tanks were connected in an oil circulation system that facilitates homogenization of gas concentrations in oil at controlled circulation rate. A relay placed between oil tank and conservator ensured the safety of electric circuit in case of uncontrolled gas generation and overflow of oil.

A needle-plate electrodes were fixed on the invert side of the top cover on the main tank, it was connected to the high voltage circuit through the bushing. The distance between the needle and the plate was adjustable. The high voltage circuit consisted of an autotransformer (0-400 V AC), a high voltage transformers (0-100 kV), an earthing motor, security fences with warning lamps, electronic circuits and a control panel.

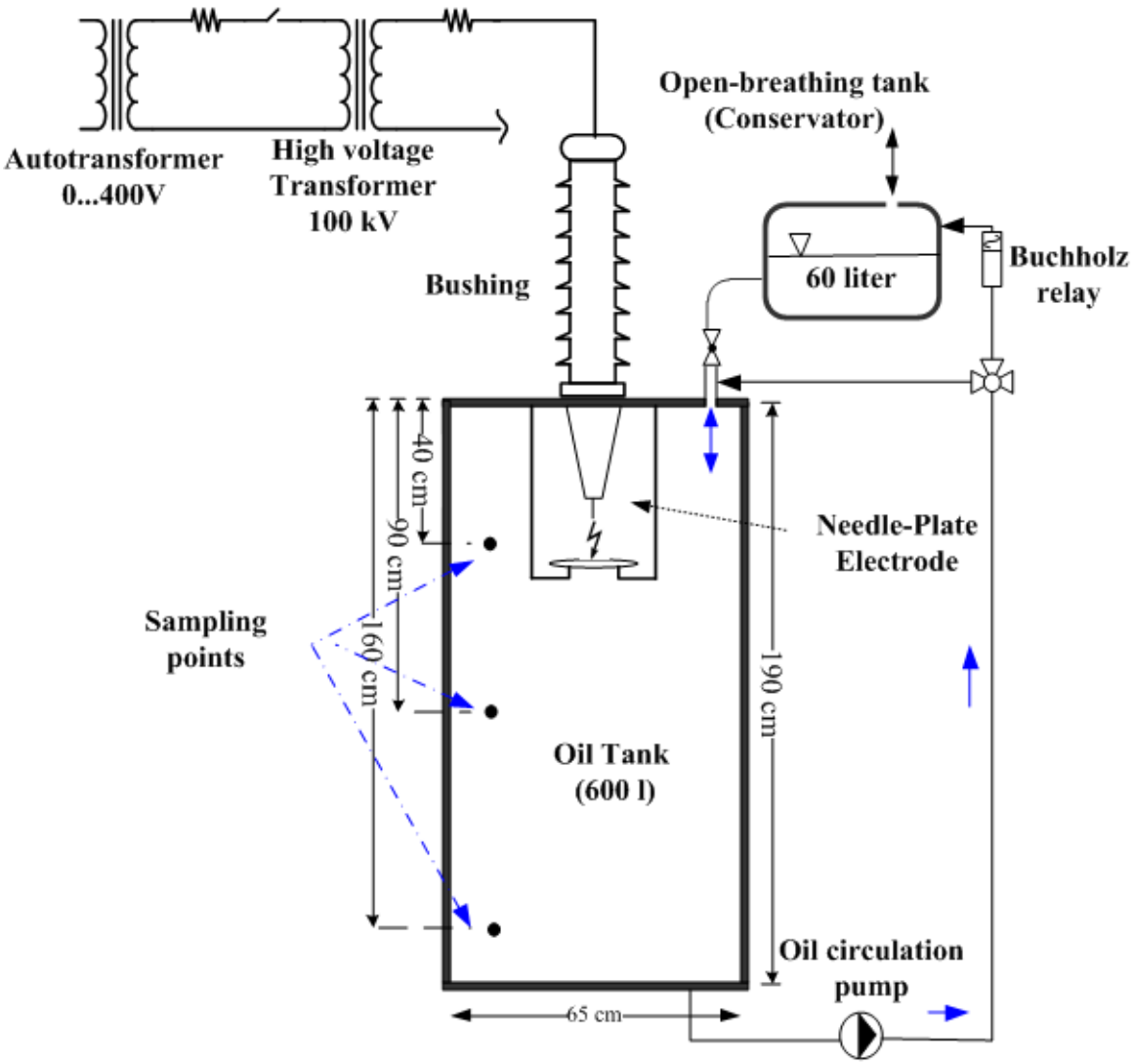

Figure 3.4: High voltage supply circuit for electric discharges in the oil tank (600 liter)

3.2.2 Oil circulation system

The oil circulation in transformers is engineered to regulate the oil temperature by continuous mixing. The oil circulates through cooling ducts of suitable dimensions to ensure the heat exchange. The rate of oil circulation depends on the dimensions of the transformer. The oil circulation system is also facilitates homogenization of gas concentrations as well as filtering and degassing of the oil in the tanks. The figure 3.5 shows a diagram of the oil circulating flow system including measurement technologies. The system was composed of a pipe network that includes 15 magnetic valves (solenoid valves) and a pump. The flow rate of the pump was adjustable up to a maximum limit of 3 l/min.

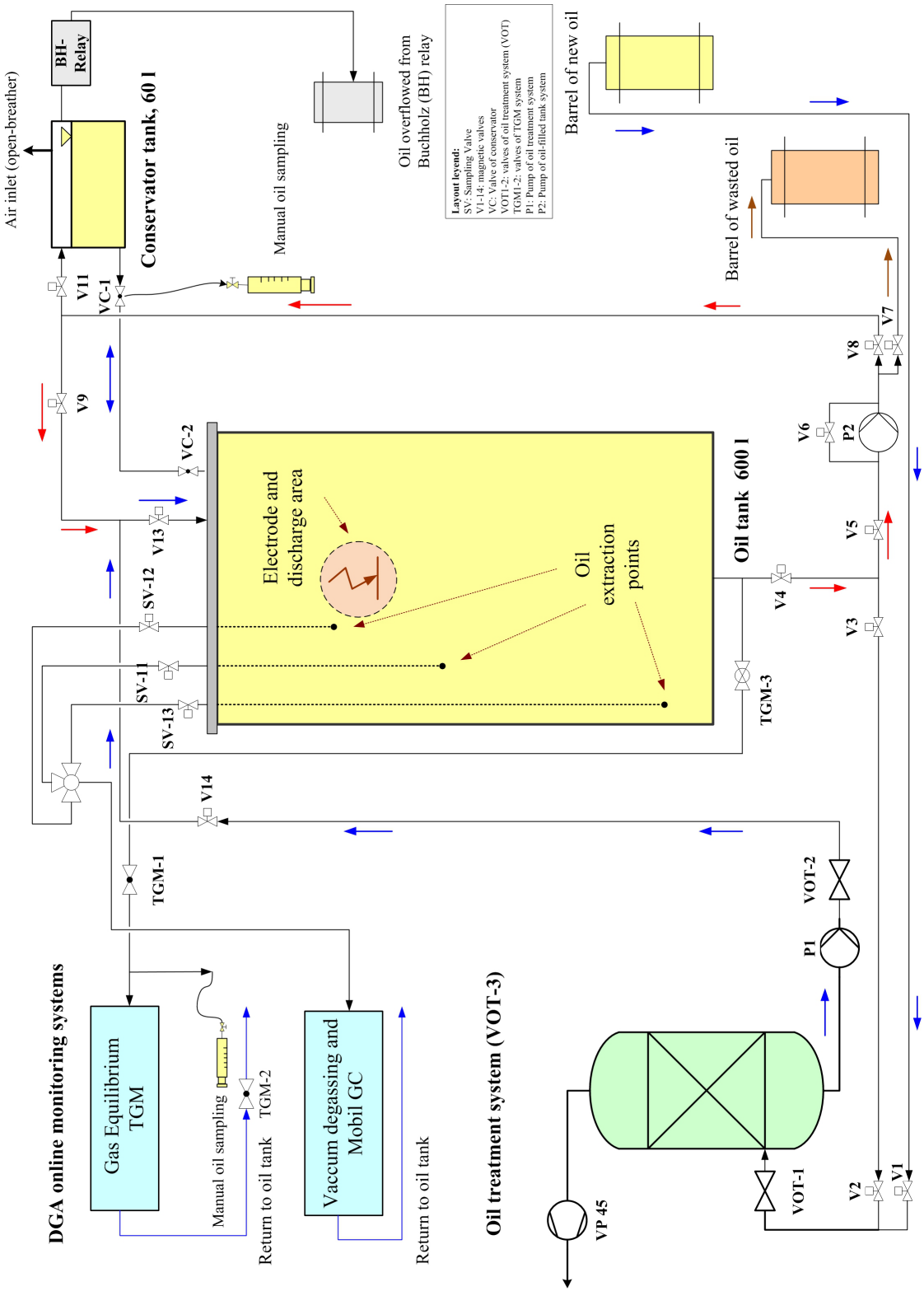

Figure 3.5: Schematic view of oil circulation system for the large setup

The volumetric flow of a fault gases can be described by principles of fluid hydraulics in the oil balance of a transformer [Altmann, 2004]. The oil balance is a dynamic system that consists of main tank and conservator tank filled with oil. The temperature of the oil in the oil balance system is regulated by means of its flow circulation through an external cooling system. Additionally, temperature gradients caused by faults at particular locations in the main tank can also lead to oil circulation due to local convection processes. This convection process due to temperature gradient is known as natural cooling flow or thermosyphon [Altmann, 2004].

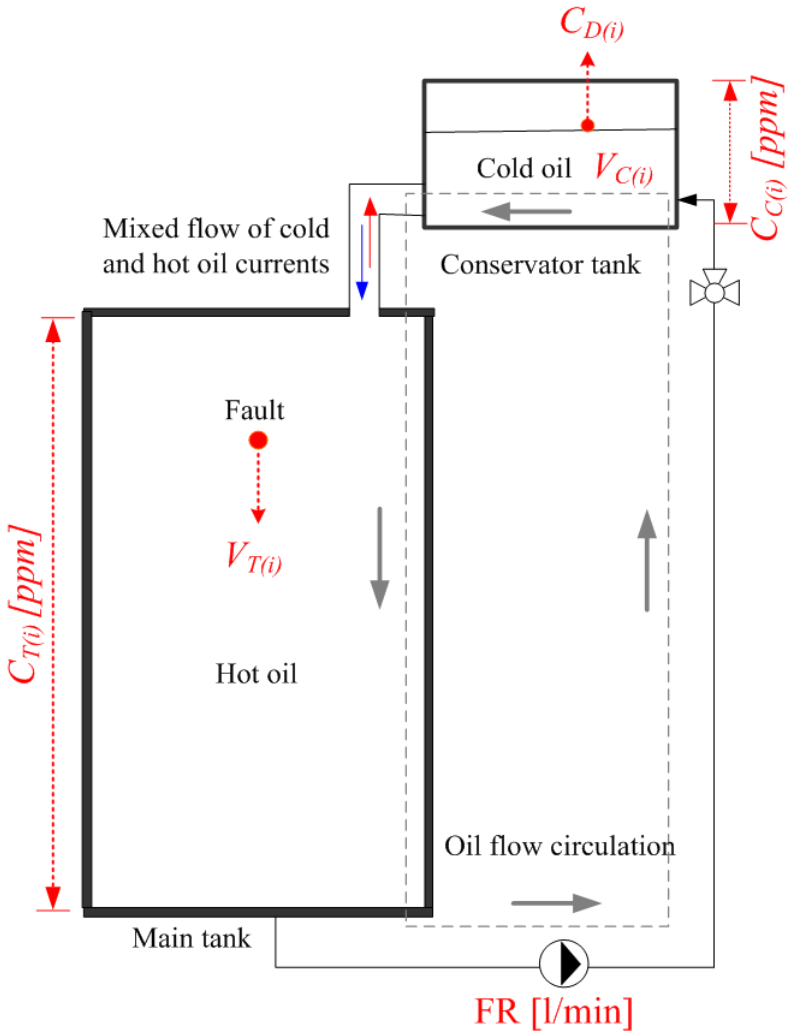

Figure 3.6: Volumetric flow of a fault gases in the oil balance of the large scale setup

The volumetric flow of a fault gases in the oil balance of the large scale setup is demonstrated in the figure 3.6. The volume of a given fault gas ($V_{T(i)}$) dissolved in oil can be expressed by its concentration gradient ($C_{T(i)}$), which

varies with time, mixing velocity and solubility of that particular gas. The volumetric flow of the fault gas is transferred to the conservator ($V_{C(i)}$) at a specific pump flow rate (FR) for oil circulation aimed at mixing of oil balance.

The concentration gradient of the fault gas ($C_{C(i)}$) in the conservator tank decreases as the gas diffuses to the atmosphere ($C_{D(i)}$). At the same time, the oil balance keeps on circulating, mixing and transferring certain amount of gases out of the oil balance, which results in an ongoing decrease of the fault gas concentration in the oil balance until the diffusion process reaches its equilibrium.

3.2.3 Automation system

This system was built to control and assess the various parameters of the experiments. A general scheme of this systems can be seen in the figure 3.7. The system consists of a remote control computer, a control terminal box and a customized software. The control terminal box is composed of digital and analog modules that transform MODBUS messages to electronic signals and vice versa. MODBUS is a typical automation application for communication between devices and data exchange. A remote control computer with a customized software registers the data conveyed by MODBUS messages and convert computer commands to MODBUS messages. The main function of the automation system was to control high voltage parameters, to regulate the oil circulation by controlling valves and to record data from the sensors that measured oil temperature, pressure and oil level in the tank.

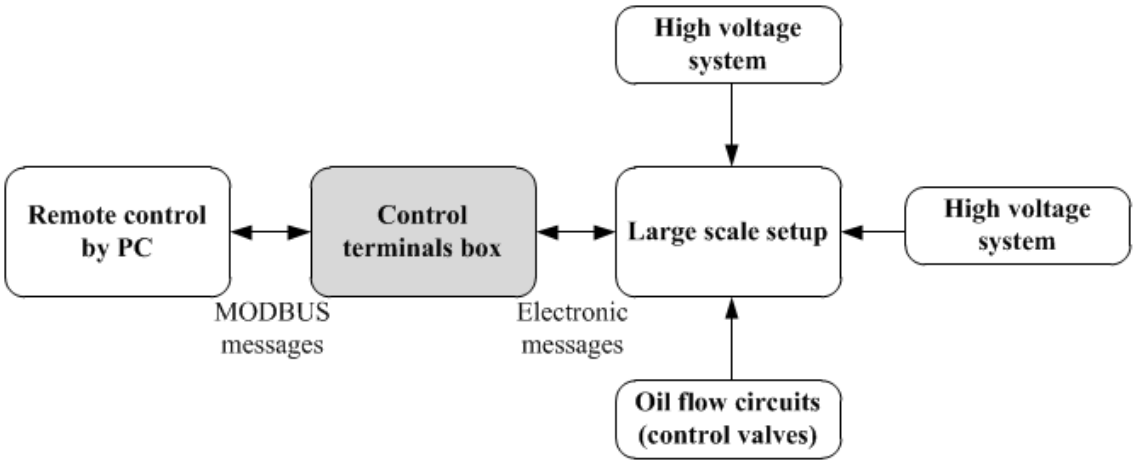

Figure 3.7: Interaction scheme of the automation system for the large scale setup

3.3 The DGA equipments

3.3.1 Kelman Transport X

Technology supplier: General Electric Company, Monitoring and Diagnostic (former Kelman Ltd., U.K.)

This is a portable gas analysis device (figure 3.8) based on the principle of photo-acoustic spectroscopy (PAS) which can detect gas-in-oil concentrations of characteristic gases such as methane, ethane, ethylene, acetylene, carbon dioxide and carbon monoxide, and moisture within a range between 1 to 50000 ppm with accuracy of approximately $\pm$ 2 ppm. Since the PAS can not detect the atomic structure of hydrogen, the hydrogen concentration is determined by a semiconductor sensor (SnO_2) which can measure up to 5000 ppm of hydrogen concentration. The measurements are conducted at 50 °C using 50 ml of oil sample and approximately 5 ml of gas sample [Kelman Transport X Infoblat, 2009].

The PAS measurements are based on the facts that absorption of infrared

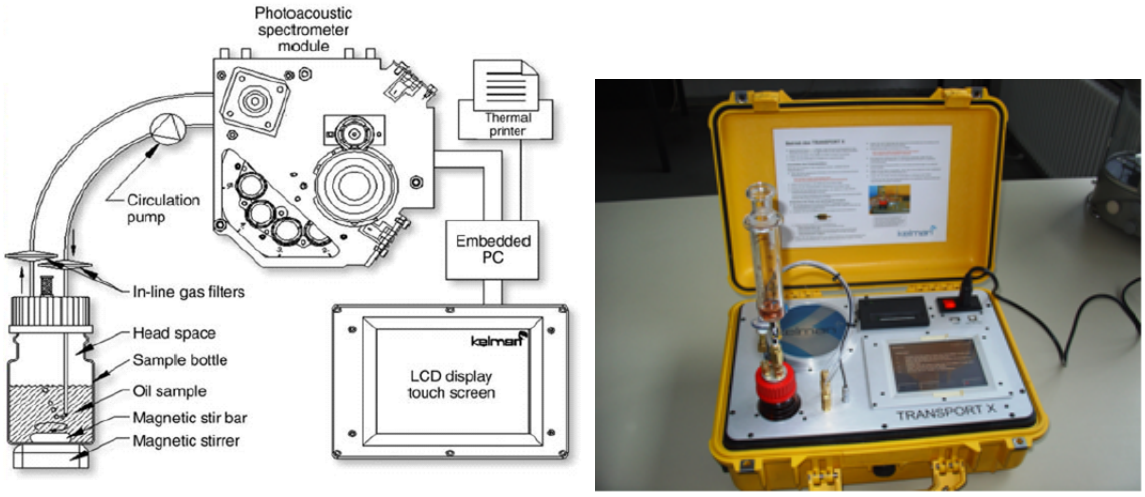

Figure 3.8: Measurement principle of Kelman Transport X,[Kelman Transport X Infoblat, 2009]

light cause heat-expansion of a gas and that each gas absorbs only a specific infrared light spectrum. Therefore, a particular sound wave produced by expansion of a gas can indicates the type of the gas and the intensity corresponding to the sound wave indicates the concentration of the gas [Cargol, 2005].

To perform the measurements oil samples are injected into a sample bottle using a glass syringe. After an assessment of temperature the oil is stirred and circulated for certain time in order to induce partitioning of dissolved gases and oil. Once the equilibrium is achieved, the gases accumulated in the headspace are analyzed by the photo-acoustic spectrometer (PAS). The results are displayed on in-built screen and recorded in the device memory.

3.3.2 Vacuum degassing and gas chromatography system

Technology suppliers: ECH Elektrochemie Halle GmbH and Energy Support GmbH, Germany.

This is an automated system composed of vacuum degassing device and mobile gas chromatograph (Mobil GC), connected by a pump and tube (figure 3.9). This system can function as an online DGA-monitoring system to conduct automatic and continuous gas-in-oil analysis following a defined measurement plan controlled by its software. The system can detect hydrogen, methane, oxygen, nitrogen, carbon monoxide, carbon dioxide, acetylene, ethane, ethylene, ethane, propane and propylene. The detection limits of the device are: 1 ppm for hydrogen, 0.2 ppm for methane and carbon oxides, and 0.1 ppm for acetylene, ethylene and ethane.

In case of a manual operating mode, the oil samples are first injected into a vacuum degassing device using a 100 ml glass syringe. The vacuum degassing device performs the extraction of dissolved gases by means of diaphragm pumps. The process of degassing occurs in a pressure range between 2 to 200 mbar in several cycles and it last for approximately 2 min. Its principle is based on the standard norms IEC 60567.

The mobile gas chromatographer (Mobil GC) performs the measurements of gas-in-oil concentrations. The extracted gas sample is automatically pumped (or a ready gas sample can be injected using a syringe) into a six-ports sample loop valve of the device. The sample loop valve controls the flow through the specific columns and detectors of the chromatographer.

Separation of different gas components occurs inside two capillary columns (carboxen and molesiev). The detection of gas concentrations is achieved by means of a thermal conductivity detector (TCD), a methanizer detector and a flame ionization detector (FID). High pressure portable gas cylinders attached to the device allow its portable use for long periods (more than 80 hours).

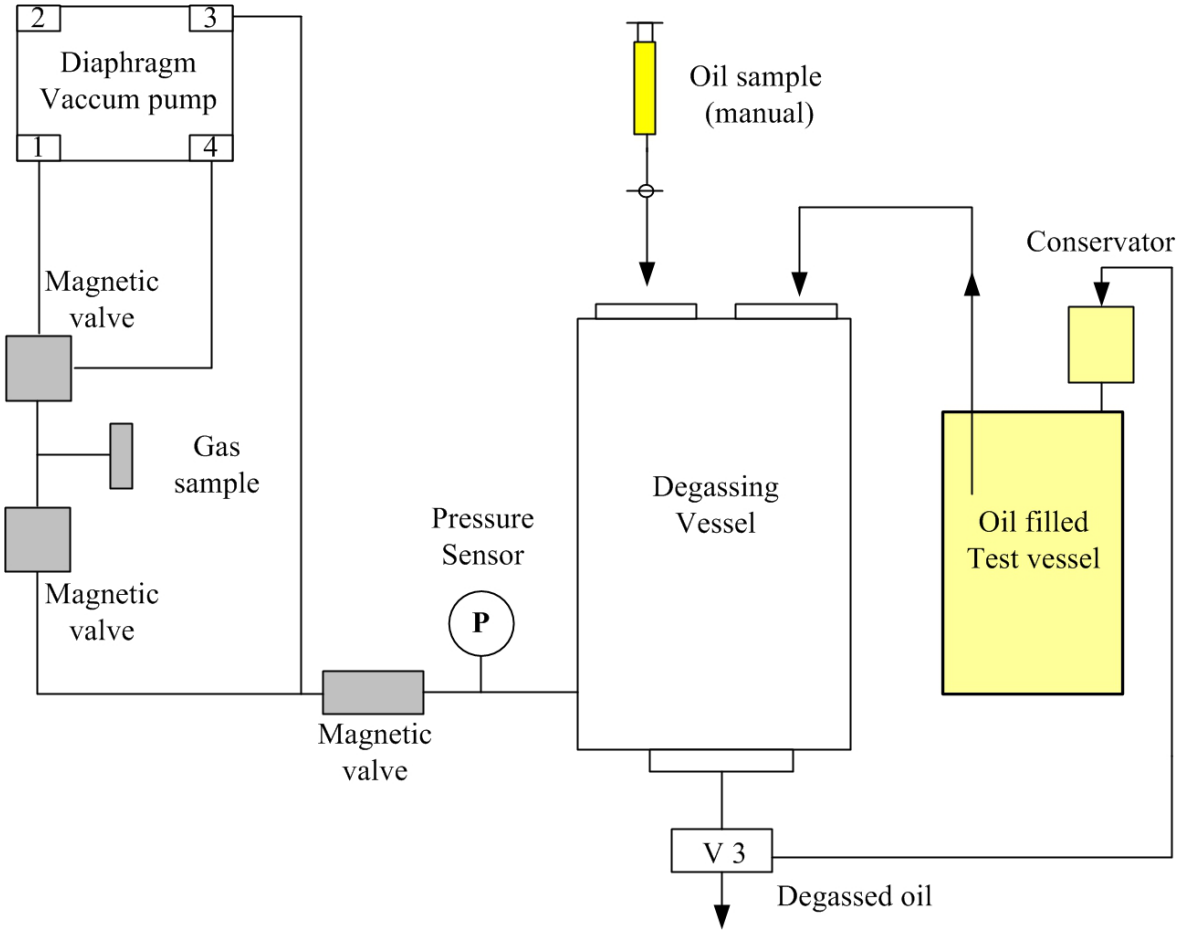

Figure 3.9: Description of vacuum degassing system [ECH Elektrochemie Halle GmbH]

3.3.3 Shaking syringe system for gas extraction

Technology suppliers: ECH Elektrochemie Halle GmbH and Energy Support GmbH, Germany

In this system a specially designed syringe is used for manual extraction of dissolved gases. The system is based on the partial degassing method described in the international standard IEC 60567.

The figure 3.10 presents the details of the syringe used for the system. The syringe has a metal plunger that can be locked in two different positions: first one is at 40 ml volume, and second one is to produce the vacuum headspace. After filling the syringe with an oil sample, the plunger is locked at the second position. Then the oil filled syringe is shaken manually for a certain time

to induce partitioning of the oil sample in oil and gas phases. The syringe is then placed standing vertical in order to allow equilibrium conditions between the two phases and let the gases to accumulate in the headspace. After the equilibrium is reached, the plunger of the syringe is unlocked and left free in order to let internal pressure equalize with the atmospheric pressure. In the following step the gases accumulated in the headspace are extracted with another syringe and analyzed by means of a gas chromatographer.

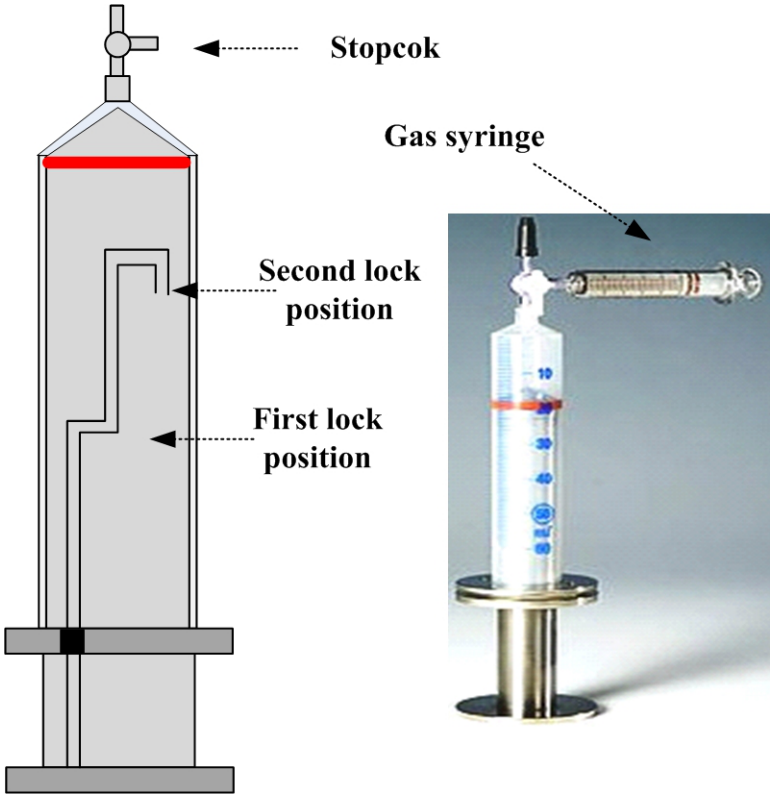

Figure 3.10: Shaking syringe used for manual extraction of gas-in-oil

The concentrations of gases dissolved in the oil can be determined according to the following principles. Under equilibrium conditions, the mass balance equation can be used to express the relationship among the concentration of gases remaining in oil (C_l), the concentration of gases in the gas phase (C_g) and the initial concentration of the gases in the oil (C_l^0) as following [Ioffe et. al., 1984]:

$$C_l^0 V_l = C_l V_l + C_g V_g \tag{3.1}$$

Where, V_l = 40 mL (volume of the oil sample) V_g = volume of the gas (measured with the shaking syringe after gas extraction and compression)

The concentration of a given gas partitioned between two phases at equilibrium conditions can be expressed as [Ioffe et. al., 1984]:

$$K = \frac{C_l}{C_g} \tag{3.2}$$

Where, K = solubility factor calibrated for the shaking method

After rearranging the equation 3.1 the concentration of gas-in-oil can be determined by the equation 3.3.

$$C_l^0 = C_g \frac{V_g}{V_l} K \tag{3.3}$$

The solubility factors presented in the table 3.1 were provided by the technology supplier (Energy Support GmbH). These coefficients are generally determined experimentally based on oil standards [ASTM Test Method D2780] or calibrated according to a particular method.

Table 3.1: Solubility factors for gases, calibrated for the shaking syringe extraction method

Gas component	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	O_2	N_2
Solubility factors	1.6	2.5	9.0	6.1	4.7	1.7	4.1	1.5	1.4

3.3.4 Transformer Gas Monitoring (TGM) system

Technology suppliers: GATRON GmbH, Germany

The technology of the transformer gas monitoring system (TGM) consists of an automated equilibrium gas headspace device in which the equilibrium of the phases can be continuously generated inside its gas provisioning column (GPC). This column represents the core of this device where the partitioning of dissolved gases between the oil and headspace takes place under equilibrium conditions. The scheme of this system is provided in figure 3.11.

The TGM can determine gas saturation contents for hydrogen, oxygen, nitrogen, carbon dioxide, carbon monoxide as well as the sum of hydrocarbons. The gas extraction is based on the natural internal standard (NIS) which specifies that pressure and nitrogen concentration in an equilibrium gas headspace are comparable to those in the atmosphere [Aragón-Patil et

al., 2007]. Hence, an equilibrium condition in which the nitrogen concentration is approximately 66000 $\pm$ 5 % ppm (average concentration) can be asssumed as the saturation condition for the other gases dissolved in the oil [Bräsel, 2005].

When this system is set for a given measurement, the equilibrium gas head space is produced and the related parameters are measured. Further the gas samples from the equilibrium headspace are extracted and analyzed using chromatography. The resulting gas concentrations are then given in to a software that determines the final gas-in-oil concentrations according to the measured parameters, such as pressure of oil solution in the gas provisioning column, oil temperature as well as certain calibrated solubility factors.

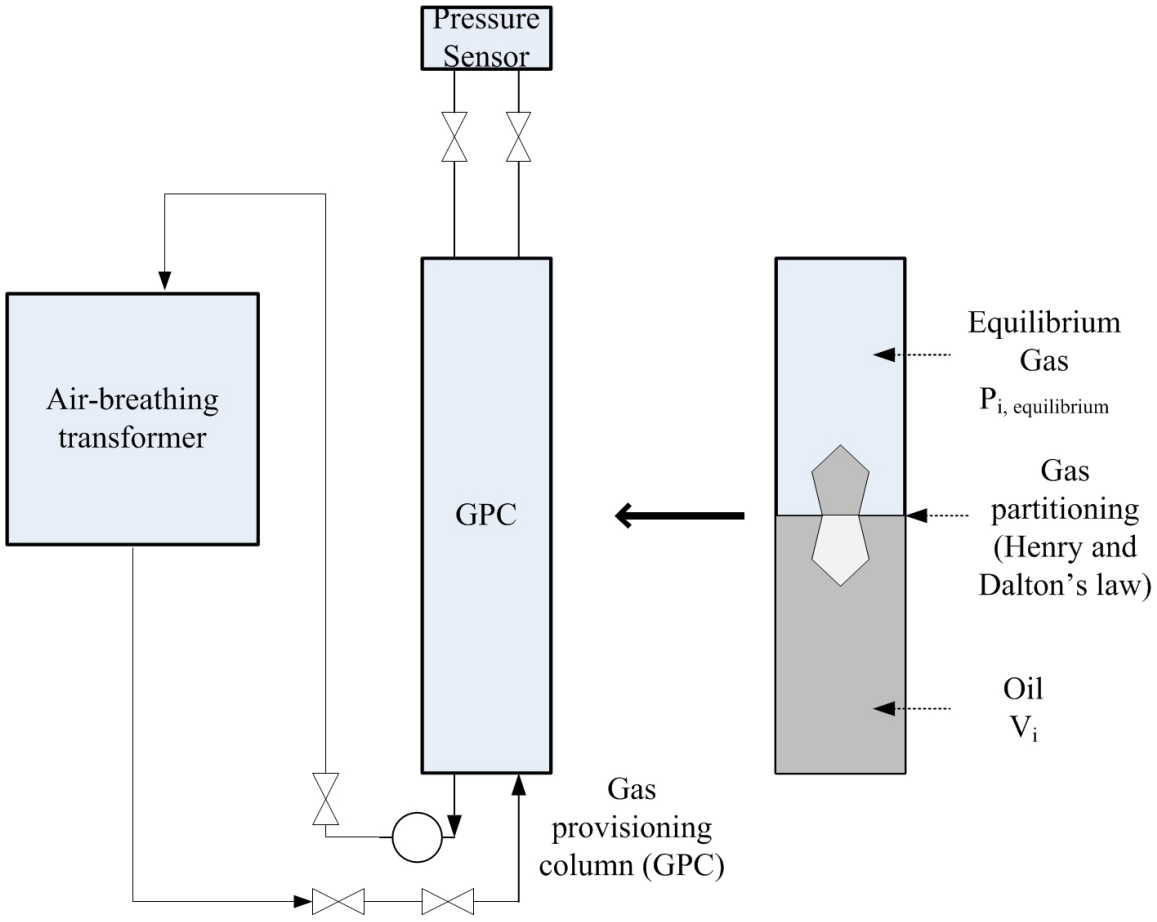

Figure 3.11: Measurement principle of transformer gas monitoring system (TGM)

3.3.5 Variable Oil Treatment (VOT-3) system

Technology supplier: Micafil AG, Switzerland

This system performs automatic oil treatment or reconditioning such as filtration, degassing and drying of oil. The VOT-3 system was included in the large test setup (see figure 3.5) mainly for reconditioning of oil. It was also used for filling and emptying the oil tank and as an intermediate container for the oil circulation system. The VOT-3 system can treat approximately 300 liter of oil per hour.

3.3.6 Mtronix partial discharge (PD) measurement system

Manufacturer: Omicron electronics GmbH, Austria

The conduction of partial discharge experiments was controlled by means of application of this system which consists of a coupling device, acquisition units, an optic fiber controller and a software (Mtronix), see figure 3.12.

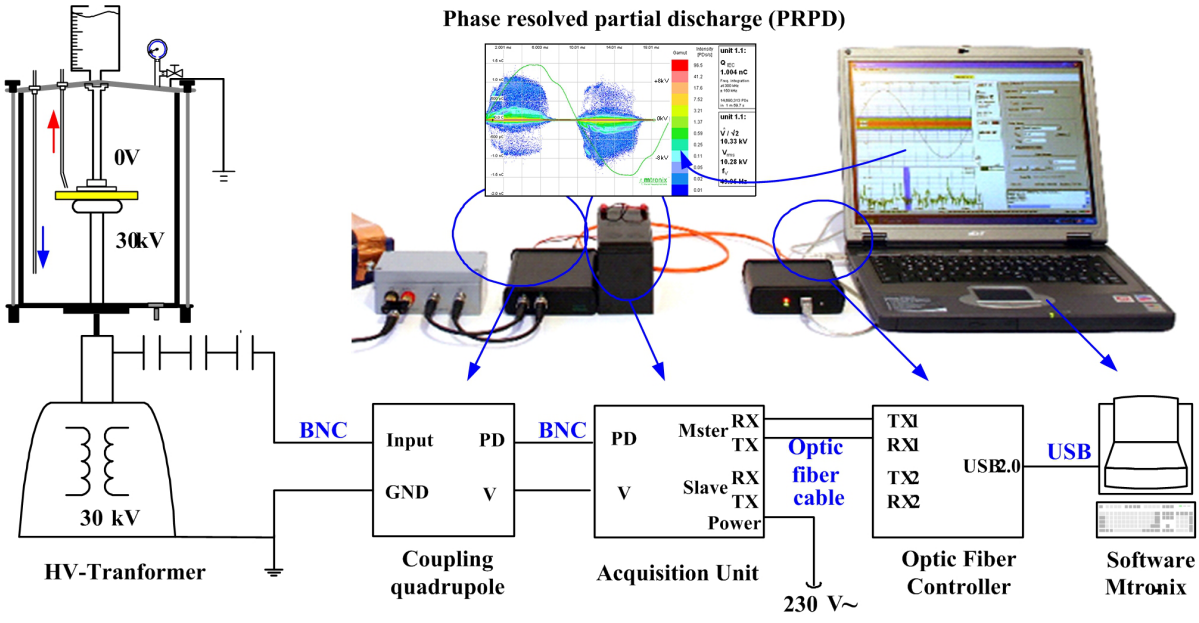

Figure 3.12: Partial discharge control and measurement system for the small test setup

The coupling device is a four-terminal network (quadrupole) that converts the input currents to output voltage signals. These signals are transmitted to

the acquisition units. The acquisition unit in connected to the fiber optic controller via fiber optic cables and coaxial connectors. The monitoring system can record and store data from PD events in real time at 25 frames per second.

The partial discharge (PD) impulses can be represented as phase resolved partial discharge (PRPD) patterns. The PRPD patterns consist of diagrams pertaining to phase curve, amplitude and frequency of pulses. The PRPD provides a reliable assessment of average charge and voltage of a partial discharge event.

The figure 3.13 presents a PRPD diagram that can be interpreted according to the distribution of PD pulses of a specific intensity (the dot colors correspond to an intensity indicated on the gamut scale), the amplitude of phase voltage (green curve), and the average magnitude of charge (Q_{IEC}) and applied voltage.

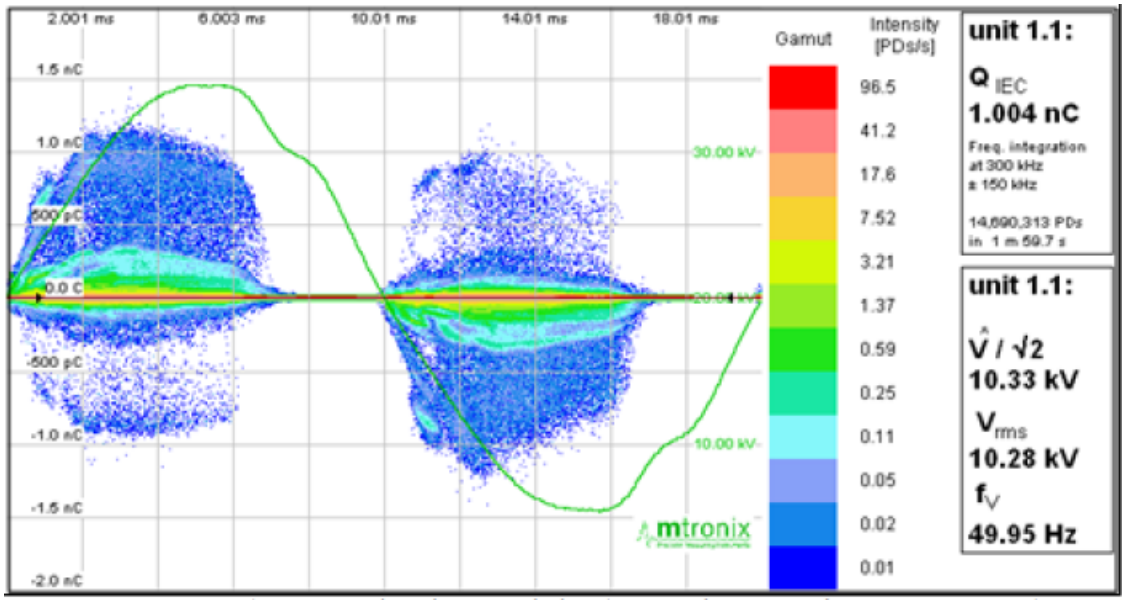

Figure 3.13: Phase resolved partial discharge diagram for a PD event (PRPD)

3.3.7 Transformer oils used for the investigations

The table 3.2 presents some of the main properties of the transformer oils used for the investigations. These transformer oils are highly refined naphtenic oils which are commonly used for oil-filled electrical equipments due to their strong resistance to degradation and oxidation. The detailed chemi-

Table 3.2: Main characteristics of the transformer oils used for the experiments

Name	**Nynas Nytro Lyra**	**Nynas Nytro 3000X**	**Nynas 10 GBN**	**Shell Diala DX**
Type	High grade Inhibited	High grade Inhibited	Uninhibited	High grade Inhibited
Kinematic viscosity at 40 °C $[mm^2/s]$	9.4	9.4	8.9	17.0
Flash point [°C]	138	135	148	136
Density $[kg/m^3]$	871 (at 20 °C)	871 (at 20 °C)	886 (at 20 °C)	877 (at 15 °C)
Pourpoint [°C]	- 60	- 40	- 57	$<$ - 60
Breakddown Voltage [kV]	40-60	40-60	40-60	$>$60

cal composition and additives in the transformer oils are not known due to confidentiality of the product information.

4 Results and Discussions

4.1 Investigations of factors affecting the dissolved gas analysis (DGA)

Dissolved gas analysis (DGA) of representative oil samples play key role in diagnostics of condition of a power transformer. Therefore quality of the oil samples is crucial for precise diagnostics. Quality of oil samples can be significantly influenced by the practices used for oil sampling and storage. The oil properties such as stray gassing and the techniques used to extract the gases dissolved in oil can also affect DGA.

Standard practices are recommended in the international guidelines [IEC 60567, 2005] to ensure adequate and systemic sampling of oil, storage of the samples and extraction and analysis of gases dissolved in oil. Occasionally these guidelines are underrated due to lack of awareness about the impact of sampling and storage related factors on DGA results. Following investigations were carried out to quantify and to remark the influence of these factors.

4.1.1 Gas-in-oil extraction techniques

Besides a proper conduction of sampling and storage of oil samples, proper extraction of gases dissolved in oil is very crucial for precise assessment of the oil conditions. In order to study the influence of the extraction techniques on the measurements of gas-in-oil concentrations, four different extraction techniques were tested and evaluated.

The extraction techniques and other experimental conditions are listed as following:

- Extraction by vacuum (VE), shaking syringe (SS), equilibrium head space (EHS) and dynamic head space (DHS, Kelman Transport X)
- Transformer oil Nynas Nytro 3000X, aged through electric discharges applied in the oil tank of the large test setup
- Oil samples extracted in 100 ml glass syringes at normal ambient conditions

- Sets of 5 samples were evaluated for each extraction method
- The gas concentrations for all the extraction techniques were measured using the gas chromatography from Mobil GC (Energy Support) with same calibration parameters.

The figure 4.1 and table 4.1 present the concentration and relative standard deviations for the critical gases obtained using the extraction techniques under investigations. The results demonstrate that the gas extraction technique vacuum (VE) leads to the highest gas-in-oil concentrations, which means maximum gas extraction and least loss of gases during the extraction. Thus, vacuum (VE) can be considered as a most efficient gas-in-oil extraction technique, followed by equilibrium gas head escape (EHS) and dynamic head space (DHS). The gas extraction using shaking syringe (SS) leads to the lowest gas-in-oil concentrations. The concentrations of the critical fault gases obtained using shaking syringe (SS) are in general 50 % to 60 % lower than that obtained using vacuum extraction (VE), which can be attributed to low gas extraction efficiency of the shaking syringe technique.

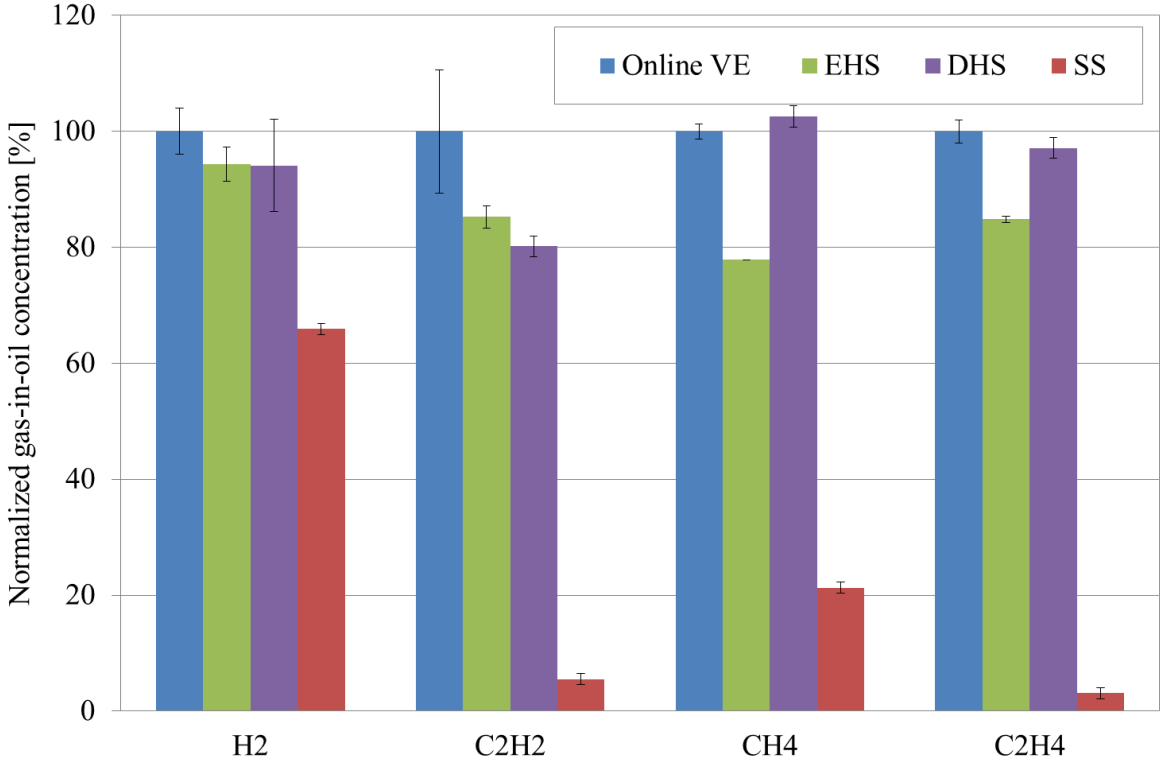

Figure 4.1: Gas-in-oil concentrations obtained using different gas extraction technics

Table 4.1: Mean gas-in-oil concentrations and relative standard deviations (RSTD) obtained for multiple measurements using different gas extraction methods

Component	Gas-in-oil concentration [ppm]				
	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Manual VE	155.8	21.8	2.1	25.4	138.5
RSTD [%]	2.3	5.3	10.2	4.5	6.3
Online VE	153.4	21.8	2.4	28.0	143.7
RSTD [%]	2.6	6.1	8.1	7.2	7.4
SS	78.9	8.86	2.4	9.84	53.60
RSTD [%]	5.0	7.8	13.6	9.8	8.9
EHS	144.8	17.0	0.0	23.6	122.5
RSTD [%]	2.1	0.0	0.0	2.1	1.6
DHS	144.4	22.4	3.2	27.2	115.2
RSTD [%]	5.5	8.1	15.2	6.6	1.6

The relative standard deviations (RSTD) indicate that equilibrium head space (EHS), with a RSTD below 2.1 %, produced the best measurement consistency for all the gases. The gas extraction carried out using syringe (SS) and dynamic head space (DHS) leads to highly inconsistent measurements, especially in the case of hydrogen ($RSTD > 5\%$). The manual and online vaccum (VE) technique show small RSTD ($< 2\%$) for hydrogen, however it is inconsistant in case of other gases.

4.1.2 Sampling of transformer oil

One of the most common problem which occurs while extracting oil samples from oil-filled transformers is the air-trapping in the oil sample in form of bubbles or free space inside the container. This issue can occur as a result of leaking pipes and valves used for oil extraction. It can also occur due to leaking or partially filled oil containers. The type of container used to carry the samples is another aspect of sampling procedure that can also affect DGA results. The effect of air-trapping and sample container was investigated using,

- Aged Nynas Nytro 10 GBN transformer oil (not-inhibited and air saturated) and
- Kelman Transport X (General Electric Company) for DGA.

Air-trapping

To investigate the influence of air-trapping on the gas-in-oil concentrations air bubbles of known volumes were added into oil samples. The gas-in-oil concentrations of these samples were then measured to quantify the influence. Following aspects were considered during the experiments.

- Oil aging: achieved by heating up the oil at 120 °C for 4 days continuously.
- Number of test samples: 50 ml oil samples each containing an air bubble of volume 0.5 ml, 1.0 ml, 2.0 ml, 3.0 ml or 4.0 ml. Three samples were prepared for each bubble volume.
- Additional samples with no air bubble were prepared as a reference oil samples.
- The samples were kept under dark and ambient conditions for 14 days before carrying out DGA.

Figure 4.2 presents normalized concentrations of hydrogen, methane and carbon monoxide for the samples with air bubbles, analyzed after 14 days.

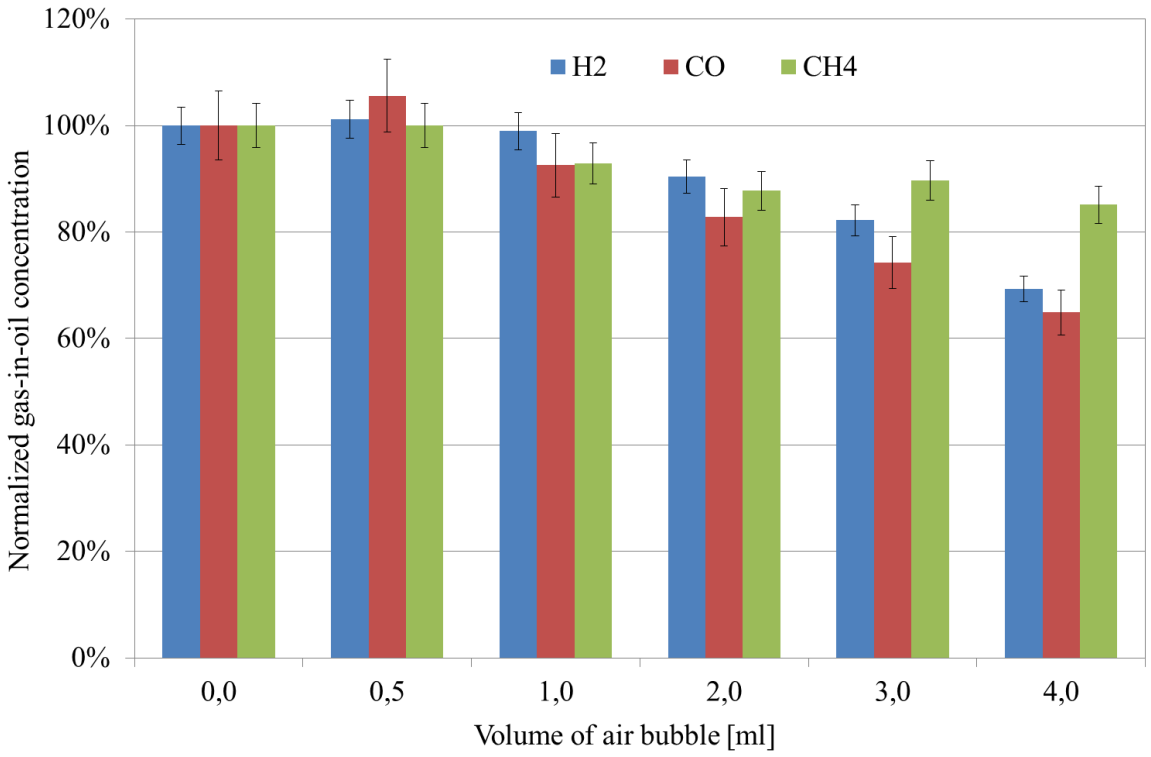

Figure 4.2: Influence of air bubbles on the concentration of stored oil samples

These gas components are among the least soluble in oil thus their concentrations presented the largest deviations due to the effect of air trapped in the sample. In general, the gas-in-oil concentrations tend to decrease as the volume of the air bubbles increases. In the case of air bubble larger than 8 % of the oil volume, the concentration of hydrogen reduces approximately by 35 %. The deviations become already significant when volume of an air bubble exceeds 2 % of the oil sample volume.

Table 4.2 shows the deviations in the concentrations of selected gases for the oil sample with air bubble of 1 ml volume. It can be observed that a 1 ml air bubble which occupies 2 % of the oil volume, causes significant reduction in the gas-in-oil concentrations in the oil sample. The concentrations of critical fault gases such as ethylene, acetylene and hydrogen showed the largest deviations.

Table 4.2: Effect of 1 ml air bubble on gas concentrations in oil stored for 14 days

Gas	Concentration of gas-in-oil [ppm]		**Deviations [%]**
	0 days	**14 days**	
CO_2	1022	940	8.7
C_2H_4	4152	2850	45.7
C_2H_2	693	605	14.5
C_2H_6	455	398	5.3
CH_4	1701	1625	4.7
CO	106	94	12.8
H_2	1187	904	31.3

Type of sampling container

In order to investigate the effect of the type of container, following two types of containers were tested:

- Air-tight glass syringes of 100 ml size
- Aluminum bottle of approximately 1 liter size

The gas-in-oil concentrations of oil samples stored in these containers for a day at ambient conditions were analyzed using vacuum degassing (VE) and gas chromatograph system (Energy Support GmbH). Table 4.3 shows the obtained results. The obtained maximum deviation of 10 % for carbon monoxide is not critical for fault diagnostics. The deviations for the critical gases are relatively small and considered to be within a tolerable range.

Table 4.3: Gas-in-oil concentrations of samples stored in gas syringes and aluminum bottles

Gas	Concentration of gas-in-oil [ppm]		**Deviations [%]**
	Glass syringe	**Aluminum bottle**	
C_2H_4	21.6	20.1	7.4
C_2H_2	80.2	78.7	1.2
C_2H_6	6.1	5.8	5.2
CH_4	15.9	15.4	3.2
CO	16.5	15.0	10.0
H_2	89.0	83.6	6.5

4.1.3 Storage conditions

The conditions of storage of oil samples, such as daylight, temperature, duration etc. play crucial role regarding the change in the gas-in-oil concentration during storage. During these investigations the influence of these factors was studied.

Daylight/darkness

The effect daylight or darkness on the oil samples was investigated under following considerations:

- Number of test samples: three
- Test period: 8 days
- Storage under daylight: samples exposed to normal daylight at normal ambient conditions
- Storage under darkness: samples stored inside a box at normal ambient conditions
- Oil aging: achieved through storage of oil at 90 °C for 4 days
- Reference oil samples: aged oil stored in dark without the influence of air bubbles.

Figure 4.3 and table 4.4 shows the concentrations of hydrogen and carbon dioxide for the oil samples stored under light and darkness. The sample of new oil stored in dark indicates a decrease in the concentration of carbon dioxide by approximately 12 %. This change can be caused by a chemical quilibrium among certain carbonic acids in the oil composition. However, the concentration of hydrogen does not show any change.

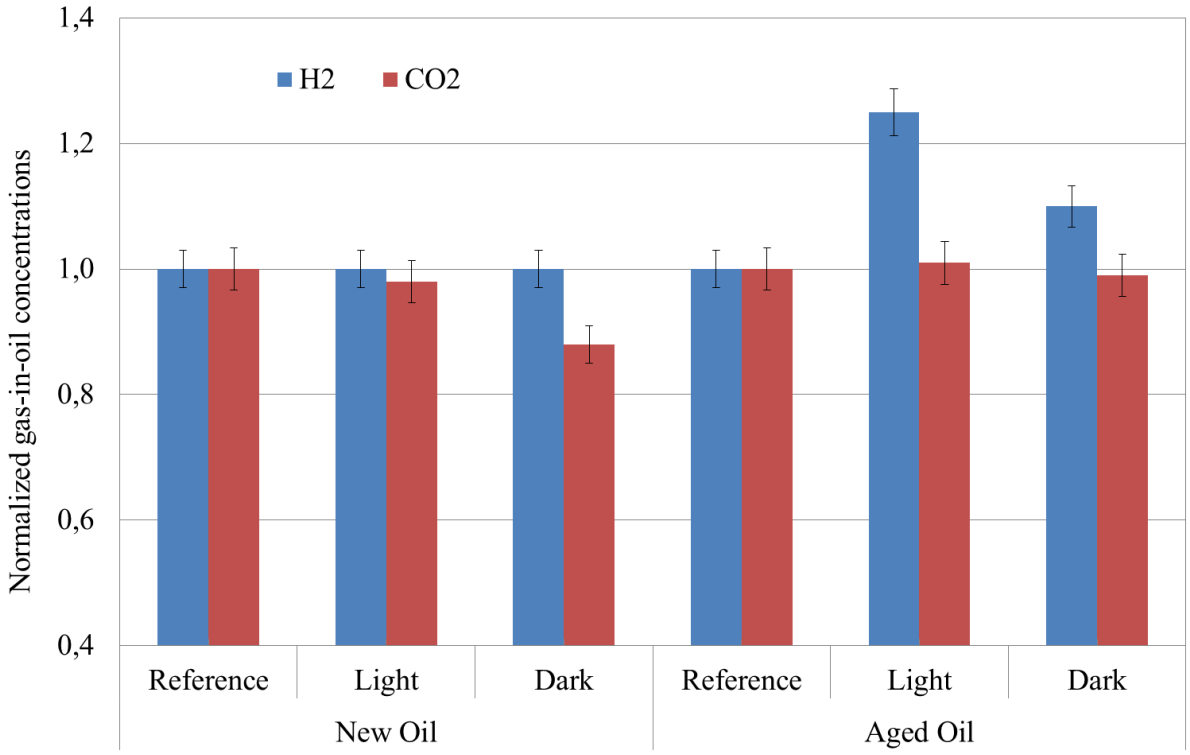

Figure 4.3: Effect of light on the concentrations of hydrogen and carbon dioxide

Table 4.4: Concentrations of hydrogen and carbon dioxide stored under light and dark

	Gas-in-oil concentration [ppm]			
Oil	New oil		Aged oil	
Condition	H_2	CO_2	H_2	CO_2
Reference	5	514	72	544
Light	5	504	90	547
Darkness	5	453	78	543

In the case of aged oil samples stored in light, there was a clear increase in the concentration of hydrogen by approximately 18 %. This increase can be attributed to photochemical reactions that involves decomposition of aging compounds in oil, such as water and acids. For the aged samples stored in dark, the concentration of hydrogen increased by 8 %, possibly as a consequence of ongoing aging and chemical reactions.

Temperature

Oil samples can undergo changes of temperature during transportation, storage or analysis itself. Experiments were carried out with samples of aged oil

stored at 7 °C, 18 °C (room temperature) and 60 °C for 7 days. The samples were stored at normal ambient conditions in darkness.

Figure 4.4 represents the gas-in-oil concentrations for hydrogen, ethylene, ethane and methane, measured after the 7 days storage duration. Results presented in the plot indicate that when the samples were stored at the temperature lower than room temperature (18 °C), the gas concentrations were not affected significantly. The results obtained from the samples stored at the temperature higher than the room temperature clearly suggest that there was a significant increase in the concentrations of hydrogen and ethane. In this particular case the increments were 12.5 % and 45 % for hydrogen and ethane, respectively. However it may vary with actual storage temperature.

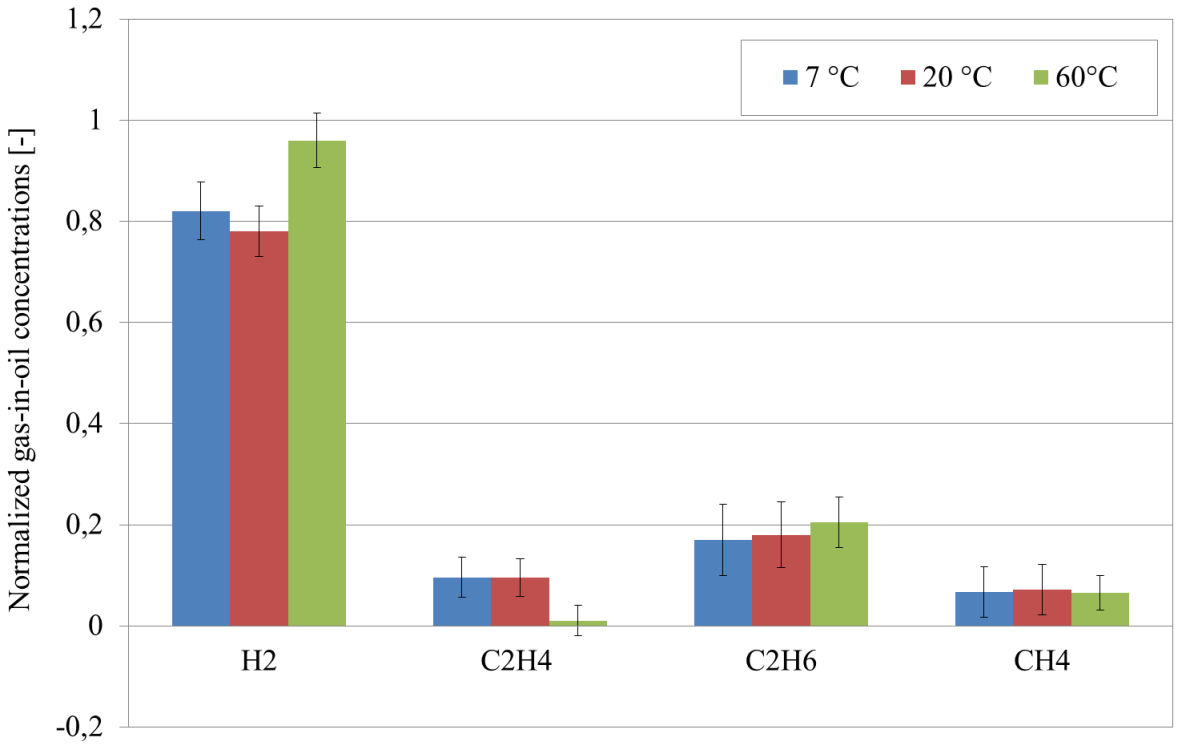

Figure 4.4: Gas-in-oil concentrations of samples stored at 7 °C, 18 °C and 60 °C for 7 days

Storage duration

In order to study the influence of storage duration on the gas-in-oil concentrations, oil samples of an aged oil were stored in dark at ambient conditions

for 16 days and monitored during the storage duration. The experiments were carried out under following conditions:

- Number of test samples: three
- Test period: 16 days
- Storage at normal ambient conditions in darkness
- Oil aging: achieved through electric faults applied to the oil.

Figure 4.5 shows the deviations in the concentrations of the hydrocarbon gases. It was found out that for adequately stored samples the gas-in-oil concentrations may deviate up to maximum 5 % after 16 days of storage. However, the measured deviations are within the error tolerence limit.

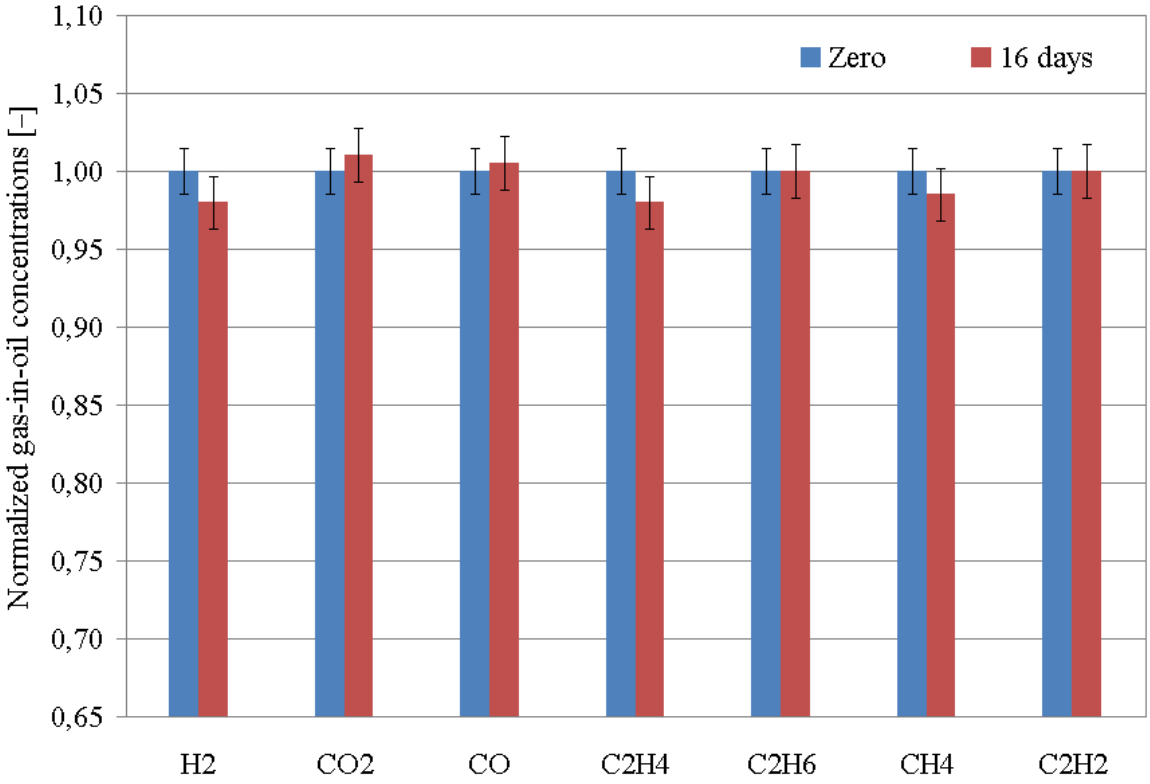

Figure 4.5: Concentrations of gases in oil samples stored adequately for up to 16 days

4.1.4 Stray gassing behavior

Certain types of oils when stored at temperatures above 60 °C can lead to fast generation rate of hydrogen, methane, ethane, carbon monoxide and carbon dioxide. This abnormal gassing behavior is known as stray gassing and it requires to be identified in order to avoid erroneous interpretation of gas-in-oil analysis. Usually non-inhibited types of oils tend to present stray gassing behavior, as for example the Nynas Nytro 10 GBN.

The tests were carried out according to the GIGRE guidelines for stray gassing oils [Griffin et al., 2005]. The methodology of CIGRE recommends preparation of samples of new (air saturated) oil with and without a copper strip which represents the copper windings inside a transformer. These samples were then placed in an oven at 90 °C for 12 days duration, during which the gas concentrations in the samples were continuously monitored.

Results obtained for the oil Nynas Nytro 10GBN are ploted in figures 4.6, 4.7 and 4.8. Rapid increase in the concentrations of hydrogen, methane and ethane in the sample with copper strip can be observed in the plots. These high gas generation rates correspond to stray gassing effect of the transformer oil. The plot in figure 4.6 is characterized by a quick increase of hydrogen concentration before reaching a plateau from which the concentration does not change further, which is the typical tendency of the oils with stray gassing behavior.

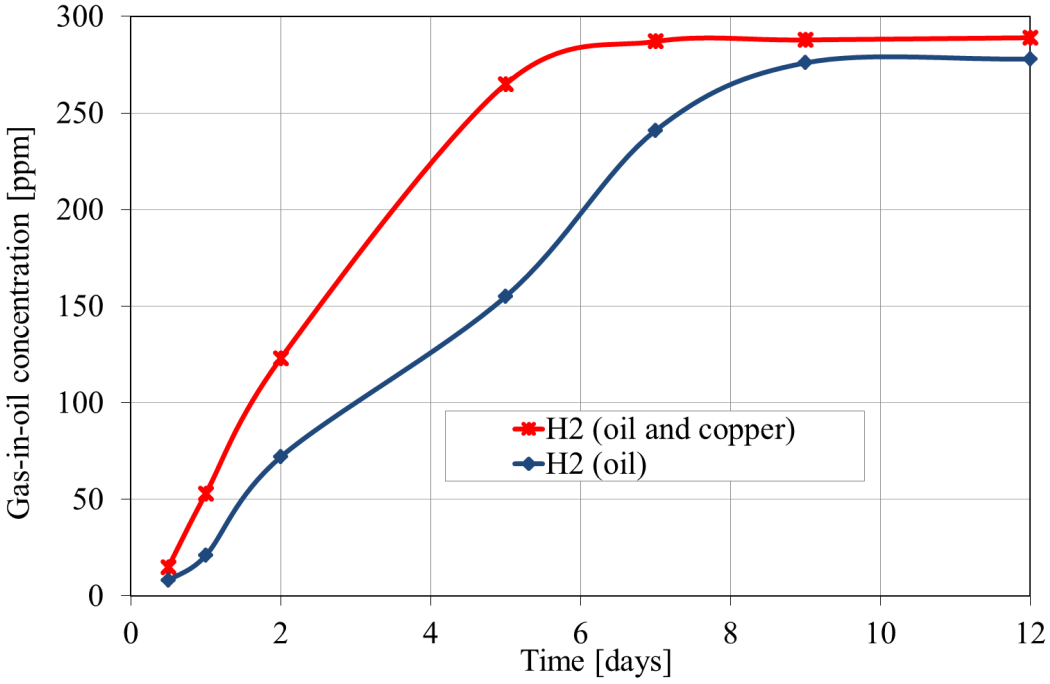

Figure 4.6: Stray gassing behavior of hydrogen in oil with and without copper

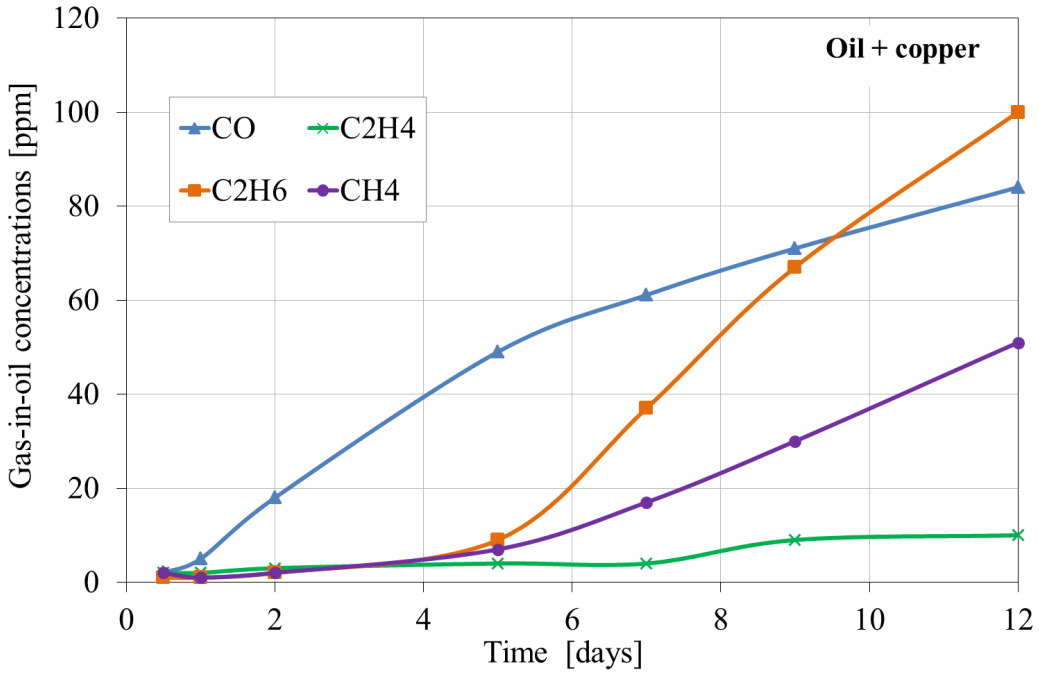

Figure 4.7: Stray gassing behavior of hydrocarbon gases in oil with copper

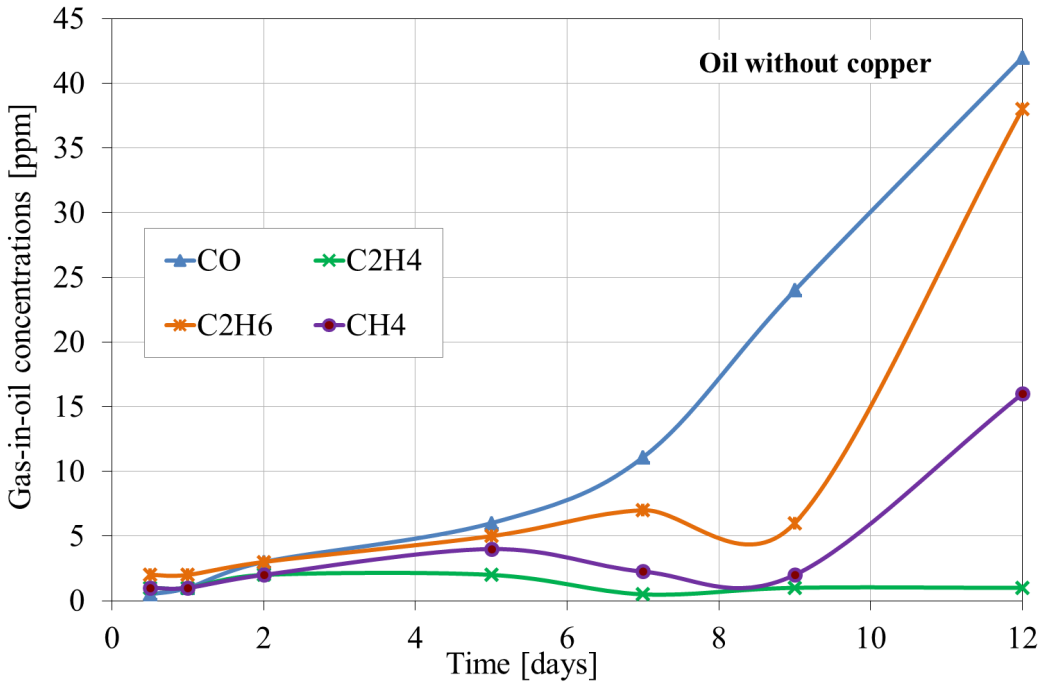

Figure 4.8: Stray gassing behavior of hydrocarbon gases in oil without copper

4.2 Experimental Investigations of Fault Gas Generation and Diffusion

These investigations were aimed at simulating the process of fault-gases generation due to electrical and thermal faults and to study the behaviour of the gases dissolved in oil using various experimental setups described in chapter 3. Typical faults, such as partial discharge, arcing discharge, and hotpot were applied on transformer oil with the purpose to produce gassing patterns. The concentrations of generated fault gases were measured using the DGA equipments mentioned in section 3.3.

The data obtained from the experiments was used to derive correlation between fault energy and concentrations of fault gases. Furthermore, in order to estimate diffusion rates of critical fault gases, diffusive behavior of the generated fault gases was also analyzed. The experiments and the following analysis of results include consideration of the know-how of measurement accuracy of the equipments and oil sampling etc., acquired during the experiments described in section 4.1.

4.2.1 Application of partial discharge (PD)

Experimental Setup

Experimental outline for the conduction of partial discharges:

- Small scale setup along with its partial discharge system (see sections 3.1.1 and 3.1.2)
- Transformer oil Shell Diala DX (12 liters); new, air saturated and at normal ambient conditions (see table 3.2)
- DGA online monitoring system (see section 3.3.2)
- PD monitoring system MTRONIXPD (see section 3.3.6)
- Oil treatment by VOT-3 system (see section 3.3.5)
- Experiments were carried out at normal ambient conditions

For the adequate application of partial discharges, the following factors required to be predefined and verified before the experiments:

1. Experimental setup was verified as PD-free after discarding possible partial discharges outside of the electrode.

2. The PD measurement system was calibrated for reliable monitoring of PD parameters
3. Oil reconditioning and adequate cleanliness of the setup were verified to avoid PD in particles.
4. The oil was kept in quiescent condition for 12 hours after filling up the test tank. In this way, it was reduced the possibility of PD created in air bubbles.
5. The sampling point for gas-in-oil analysis was located near the electrode, see figure 4.9.

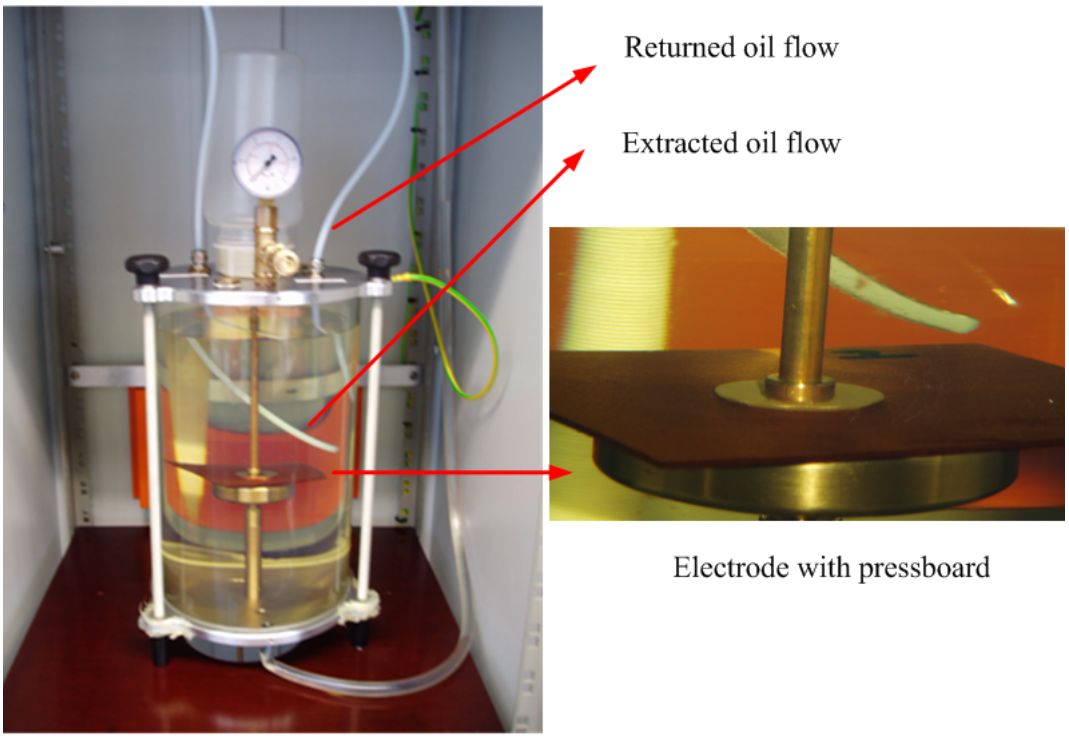

Figure 4.9: Test tank (12 liter) with the electrode setup for producing partial discharges

The table 4.5 shows gas-in-oil concentrations of fault gases measured after reconditioning of the transformer oil Shell Diala DX aided by treatment using the VOT-3 system followed by air saturation with normal atmospheric air bubbled for several hours in the oil barrel.

Table 4.5: Gas-in-oil concentration of oil after reconditioning and air saturation

	H_2	CH_4	C_2H_6	C_2H_2	C_2H_4	CO	N_2	O_2
Gas-in-oil [ppm]	5.7	1.5	8.3	7.6	5.2	9.3	56320	35330

Methodology

The PD voltage was increased in steps of 2 kV at 10 minutes interval to a voltage level at which the first discharge pulses were observed. Based on the complex stochastic properties of PD, it is known that achievement of a stable PD events with differentiated patterns requires to conduct numerous repetitions of the experiments. Over a entire period of discharge application, continuous monitoring and recording of main parameters of the PD was carried out by means of phase resolved partial discharge diagrams (PRPD) provided by the system MTRONIXPD.

Further, the voltage was increased until a maximum level where the PD pulses became more continuous and evenly distributed along the sinusoidal phase voltage. Generally, the frequency of PD pulses varies randomly in successive cycles, characterized by certain increasing or decreasing frequency with respect to time and applied voltage.

Results

After conduction of numerous experiments, two different patterns of PD (PD-1 and PD-2) were obtained in long test periods at different intensity and distribution of pulses. These patterns were identified by means of analysis of phase-resolved partial discharge (PRPD) diagrams acquired during online monitoring of the discharge patterns.

Figure 4.10 and figure 4.11 present some examples of PRPD diagrams obtained for each PD pattern. Both of the PD patterns exhibit a mean apparent charge (Q_{IEC}) of approximately 1000 pC that remained almost constant during the test period.

The pulses and discharges within a PD event exhibit stochastic character that make them differ among themselves at instant values of voltage. Thus, the estimation of total energy involved in a partial discharge event requires a statistical assessment of the total number of discharges, including their individual pulse apparent charge and instantaneous voltage during an AC voltage period [Florkowska et al., 1999].

However, due to technical limitations the statistical assessment of the huge

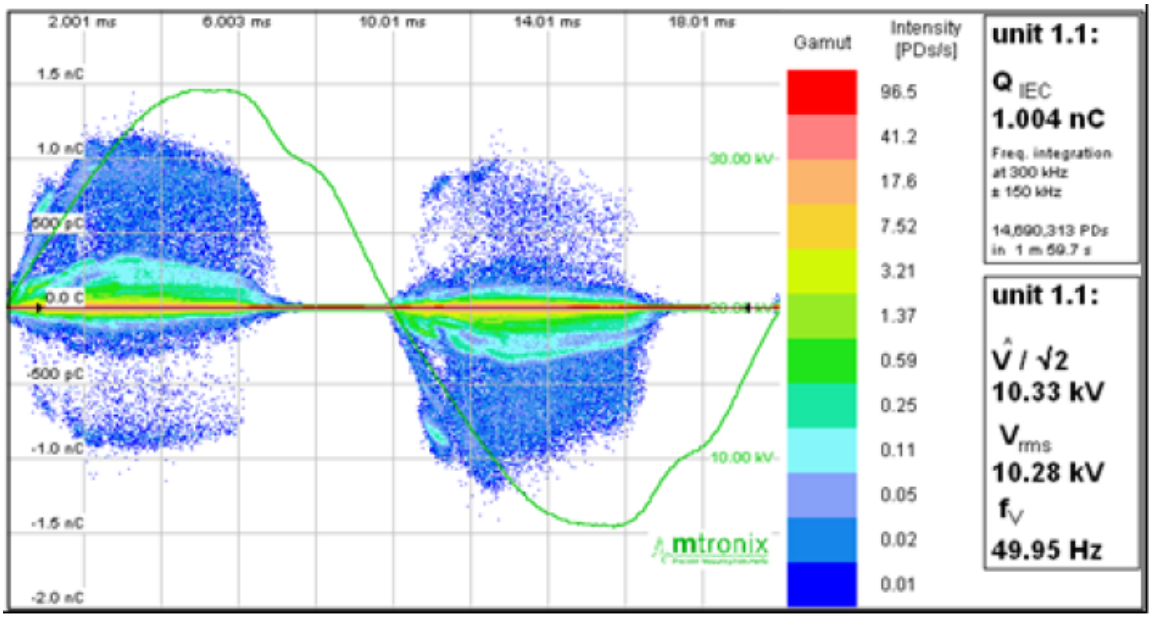

Figure 4.10: PRPD for PD experiment with applied voltage of 11 kV (PD-1)

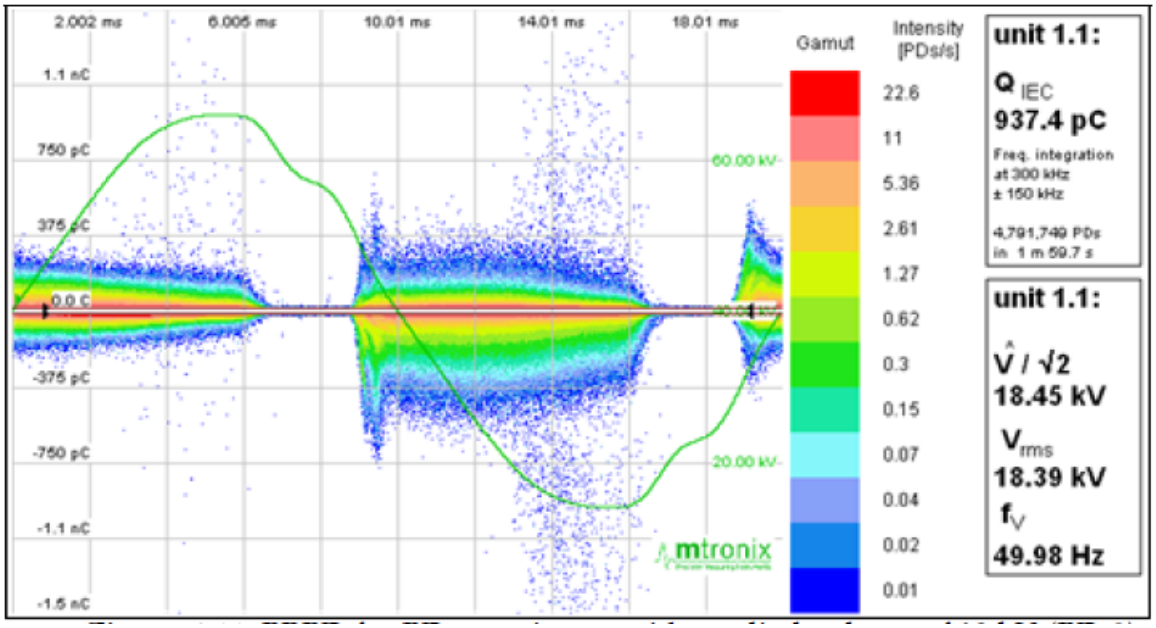

Figure 4.11: PRPD for PD experiment with applied voltage of 19 kV (PD-2)

amount of data generated during a PD event was not possible to achieve. Nonetheless, the total energy of partial discharge could have provided useful information for DGA.

The figure 4.12 present the concentration-time profile of fault gases generated during the application of the PD-1. The generation of gas-in-oil was monitored using online DGA system by taking the samples at 1 hour interval from the neighbourhood of the electrode.

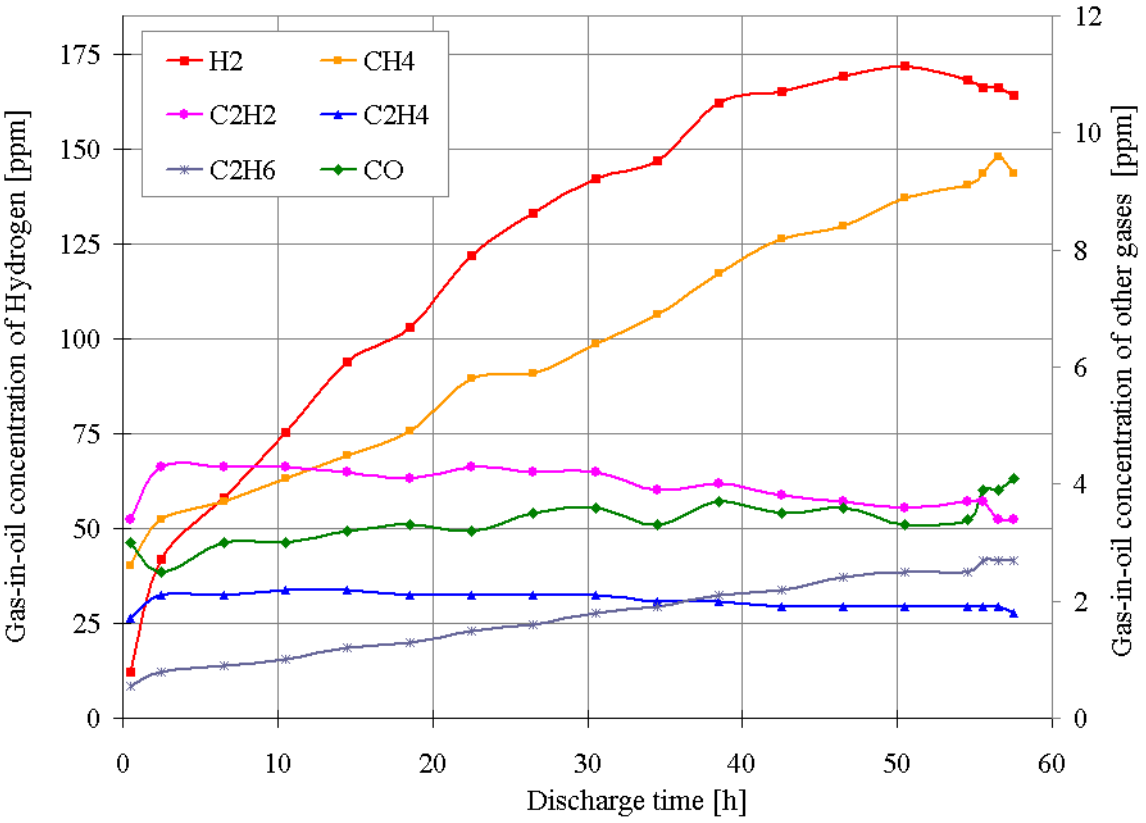

Figure 4.12: Concentration of fault gases for PD-1

The PD-1 was carried out for approximately 58 hours before stopping it manually. The PD pulses were generated in a homogeneous distribution scattered in a broad manner along the phase voltage curve at a constant applied voltage of approximately 11 kV. Most of the discharge pulses occurred without production of sparks or gas bubbles in a continuous way throughout the test period. This PD-pattern presented relative lower energy content and the generation of fault gases occurred at slow rate which allowed high dissolution of gases in oil. The highest concentration was obtained for hydrogen at about 172 ppm. Other fault gases reached maximum concentrations below 10 ppm.

The PD-2 (figure 4.13) was conducted for approximately 115 hours at approximately 19 kV of applied voltage until it was terminated by a spontaneously occurred arcing discharge. This PD pattern was characterized by the discontinuity of discharge pulses scattered in narrow shape along the phase voltage curve. Most of the discharge pulses presented higher energy content in compared to the first pattern. The PD pulses occurred erratically accompanied by powerful sparks and abundant formation of gas bubbles throughout the test period. During the PD-2 the highest measured concentration was of hydrogen, about 905 ppm. It was followed by a high concentration of acetylene

in the range of approximately 304 ppm, along with methane and ethylene above 150 ppm. Additionally, perforations on the pressboard surface were observed as a result of the intensity of discharges.

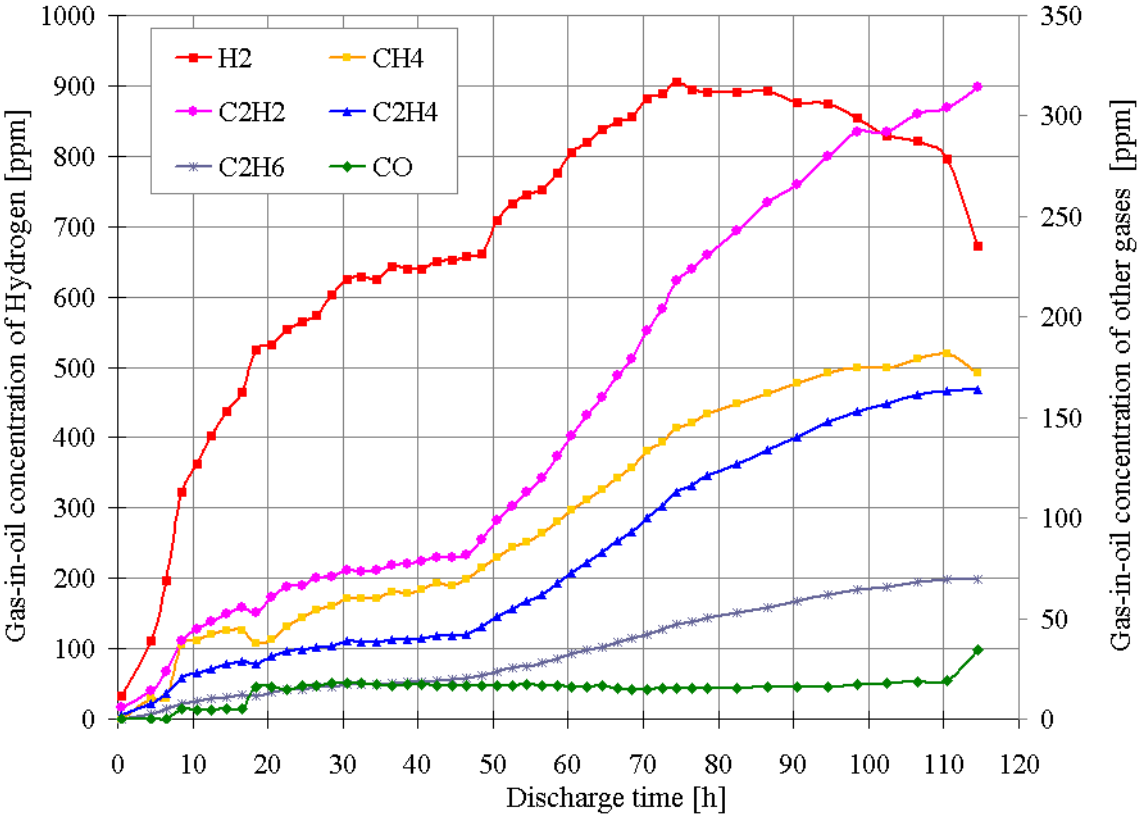

Figure 4.13: Concentration of fault gases for PD-2

Table 4.6 summarizes the most important parameters of the two PD patterns which are differed in their intensities. These two patterns correspond to PD experiments that presented the best stability during the test periods.

Verification of the course of these PD faults was carried out by means of a gas generation pattern method, which analyses the patterns obtained by plotting normalized gas-in-oil concentrations of H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2 in oil [Okubo, et al., 1999 and Tsukioka et al., 1978]. In this method the gas concentrations are first normalized by dividing each of them by the concentration of the dominant gas (with maximum concentration) among the selected gases. Thus, the dominant gas is always represented by normalized concentration of 1.0 [-]. Then these normalized concentrations are plotted in the sequence: $H_2, CH_4, C_2H_6, C_2H_4$ and C_2H_2, as shown in Figure 4.14.

Table 4.6: Main parameters obtained for different PD patterns

Parameters or characteristics	**PD-1**	**PD -2**
Mean applied voltage, UPD [kV]	11	19
Mean apparent charge, QIEC [pC]	1000	1000
Discharge time, [h]	58	115
Characteristics of PD pulses	Concentrated, high frequency of pulses	Scattered, low frequency of pulses
Collateral effects during PD	Not observed	Sparks, gas bubbles, arcing discharge
Pressboard condition after PD	Intact	Cracks and holes
Gas generation rate	Low	High
Dominant Gases	H_2 (172 ppm) CH_4 (9.6 ppm)	H_2 (905 ppm) C_2H_2 (304 ppm)

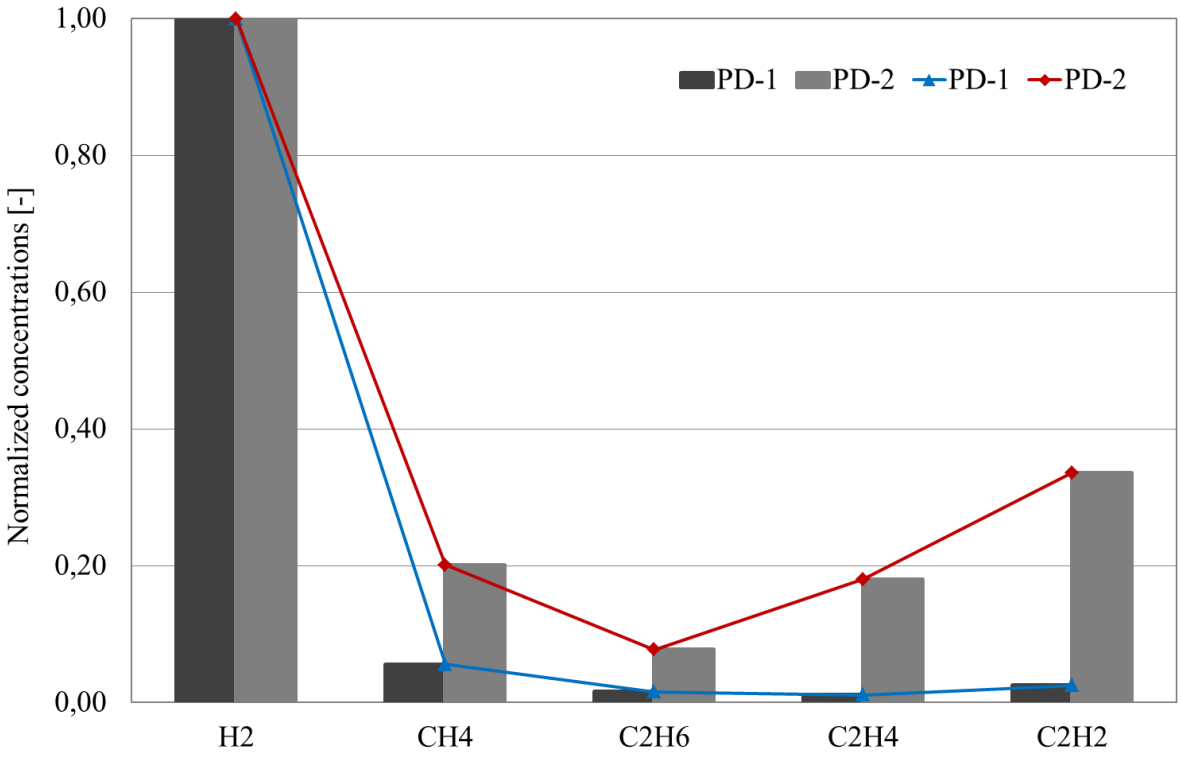

Figure 4.14: Gas concentration patterns obtained for the partial discharge experiments PD-1 and PD-2

Consequently, the pattern displayed for PD-1 indicates the typical distribution of gas-in-oil concentrations corresponding to a partial discharge fault (see figure 2.14), whereas the pattern for PD-2 shows a characteristic gas-in-oil concentrations for a discharge fault. The comparison of the gas patterns for PD-1 and PD-2 implies that these faults occurred with different levels of energy, the partial discharge fault dissipated lower energy than the discharge fault. However, due to technical limitations of the setup, it was not possible to determine the energy dissipated during these electric faults.

The fault diagnostic was also carried out by applying the CIGRE fault interpretation scheme (see table 2.8). The CIGRE scheme provides the interpretations of the fault in transformer oil based on the gas-in-oil concentrations. With already known character of the fault, the diagnostic was aimed at cross-checking the fault interpretations provided in the CIGRE scheme.

The table 4.7 shows the comparison of the key ratios and threshold values obtained for the PD experiments with those provided in the CIGRE scheme.

Table 4.7: Fault diagnostic by applying the CIGRE fault interpretation scheme (partial discharge)

Key gas	CIGRE scheme		PD Experiments	
Part I: Key gas ratios				
Key gas Key gas	**Ratio [-]**	**Fault type**	**Ratio PD-1 [-]**	**Ratio PD-2 [-]**
(C_2H_2/C_2H_6)	> 1	AD	1.35	4.49
(H_2/CH_4)	> 10	PD	19.32	4.9
(C_2H_4/C_2H_6)	> 1	OH	0.76	2.39
Part II: Thresholds [ppm]				
Key gas Key gas	**Threshold [ppm]**	**Fault type**	**Threshold PD-1 [ppm]**	**Threshold PD-2 [ppm]**
C_2H_2	> 20	AD	4	314
H_2	> 100	PD	172	905
$\sum C_xH_y$	> 1000	OH	190	1515
$\sum CO_x$	> 10000	CD	470	446

A D: arcing discharge, PD: partial discharge, OH: oil overheating, C D: cellulose degradation

Interpretation of the key gas ratios and thresholds for PD-1 experiment according to the CIGRE scheme suggests that PD-1 occurred as a partial dis-

charge event without oil overheating and damage to cellulose, which is already known from the discharge pattern monitored during the experiment. Thus, the CIGRE scheme correctly interpret the type of fault in the case of PD-1.

The interpretation for PD-2 indicates that, according the CIGRE scheme this fault occurred as a high intensity partial discharge. However, in reality the PD-2 occurred as a low intensity partial discharge followed by arcing discharge which resulted in oil overheating. Thus, in the case of PD-2 CIGRE scheme fails to interpret the fault correctly.

4.2.2 Application of hotspot (HS)

Experimental Setup

The purpose of these experiments was to generate the characteristic fault gas patterns and concentrations pertaining to local overheating due to thermal fault. The hotspot experiments were carried out under following considerations:

- Small scale setup for hot spots (see section 3.1.1)
- Hot spot materials: graphite pencil lead (2B)
- Transformer oil Nynas Nytro Lyra (12 liters); air saturated and at normal ambient conditions (see table 3.2)
- DGA online monitoring system (see section 3.3.2)
- Oil treatment by VOT-3 system (see section 3.3.5)
- DC power supply system
- Experiments were carried out at normal laboratory conditions

Before the tests, the oil was reconditioned. The table 4.8 presents the gas-in-oil condition of transformer oil Nynas Nytro Lyra after reconditioning and air saturation. The figure 4.15 presents an image of the test setup during the conduction of a hotspot fault using graphite conductor.

Table 4.8: Gas-in-oil concentration of oil after reconditioning and air saturation

	H_2	CH_4	C_2H_6	C_2H_2	C_2H_4	CO	N_2	O_2
Gas-in-oil [ppm]	5.2	0.8	12.2	10.5	4.5	9.3	57597	24407

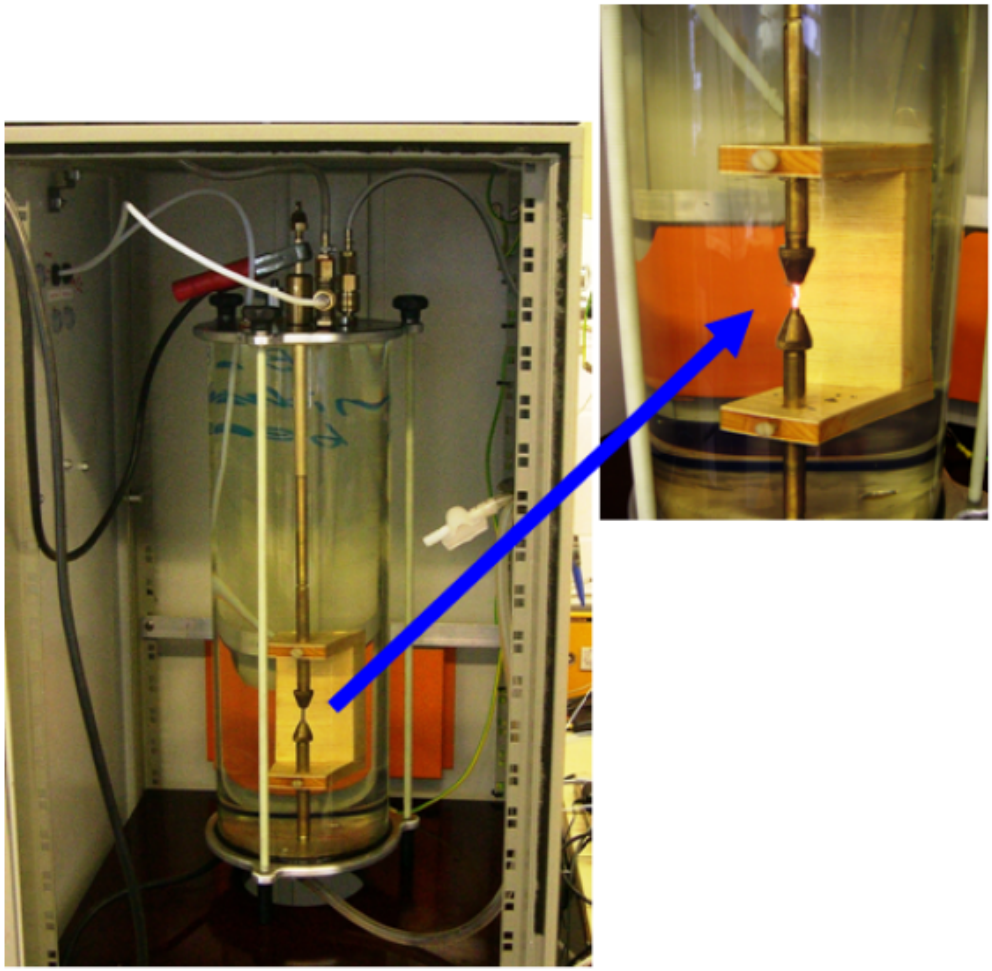

Figure 4.15: Test setup for application of hotspot in oil

Methodology

The hotspots were produced by powering a semi-conductor material at varying voltages in order to heat it up at specific temperatures, simulating a localized overheated surface inside a transformer. For this purpose a 1 cm long piece of graphite pencil lead of grade 2B was used a semi-conductor material. To power the hotspots a DC power supply (0 to 100 A) circuit that allow to control the flow of current through the piece of graphite lead was used.

The temperature of the hotspots was indirectly controlled on the basis of the current, voltage, and the resistance of the graphite lead measured using Ohmmeter. The voltage was applied for a predefined time period of 60 seconds. The resistance of this semi-conductor material at a given temperature can be determined using the equation 4.1.

Rearranging the equation 4.1 gives equation 4.2, which can be used for calcu-

lation the temperature from a measured resistance. The graphite lead used in pencils has certain amount of impurities, therefore resistivity coefficient of 3.75^{-5} Ohm.m (at 20 °C) was adopted for the estimations. Experimental parameters for the hotspot faults at different temperatures can be seen table 4.9.

$$R_T = \frac{\rho \cdot L}{A}(1 + \alpha \cdot (T - 20)) \tag{4.1}$$

$$T = \frac{1}{\alpha} \cdot (R_T \cdot \frac{A}{\rho \cdot L} - 1) + 20 \tag{4.2}$$

Where,
R_T = Resistance of graphite at a specific temperature, Ohm
ρ = Resistivity of material at the reference temperature 20 °C, (3.75^{-5} Ohm.m)
L = Length of material, (0.01 m)
A = Cross sectional area, ($4.65^{-7}m^2$)
T = Temperature, °C
α = Temperature coefficient of graphite ($4.84^{-4}1/°C$)

Table 4.9: Experimental parameters for hotspot faults

Exp. No.	HS-1	HS-2	HS-3	HS-4
Hotspot temperature [°C]	1000	750	500	300
Resistance [Ohm]	1.2	1.1	1.0	0.8
Applied current [A]	30	28	15	9
Total energy [kJ]	64	52	14	4

Results

The figure 4.16 displays the plots of gas-in-oil concentrations vs dissipated energy for hotspots faults of different temperatures. In general, the gas-in-oil concentrations increase with dissipated energy, however the plots demonstrate not-linear relationship. The plots also show that at high energy levels for the temperature above 1000 °C ethelyne concentrations in the oil increase abruptly. However, hydrogen, acetylene and ethane exhibit only minor or no changes.

The hotspot faults were analyzed using the gas generation pattern method (see figure 2.14). The normalization of gas-in-oil concentrations for a hotpot of temperature 500 °C or above was based on the concentration of ethylene, while for the hotspot of lower temperature it was based the concentration of acetylene. The figure 4.17 present a comparison of maximum gas-in-oil con-

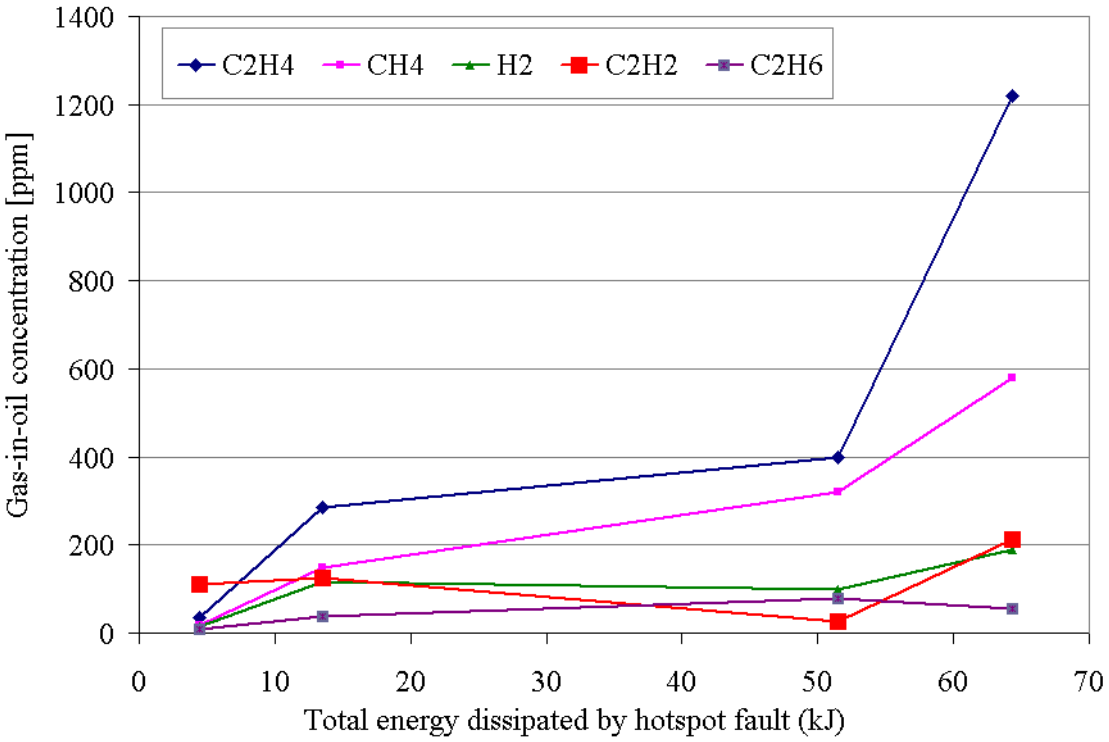

Figure 4.16: Gas-in-oil concentrations vs dissipated energy for hotspots faults

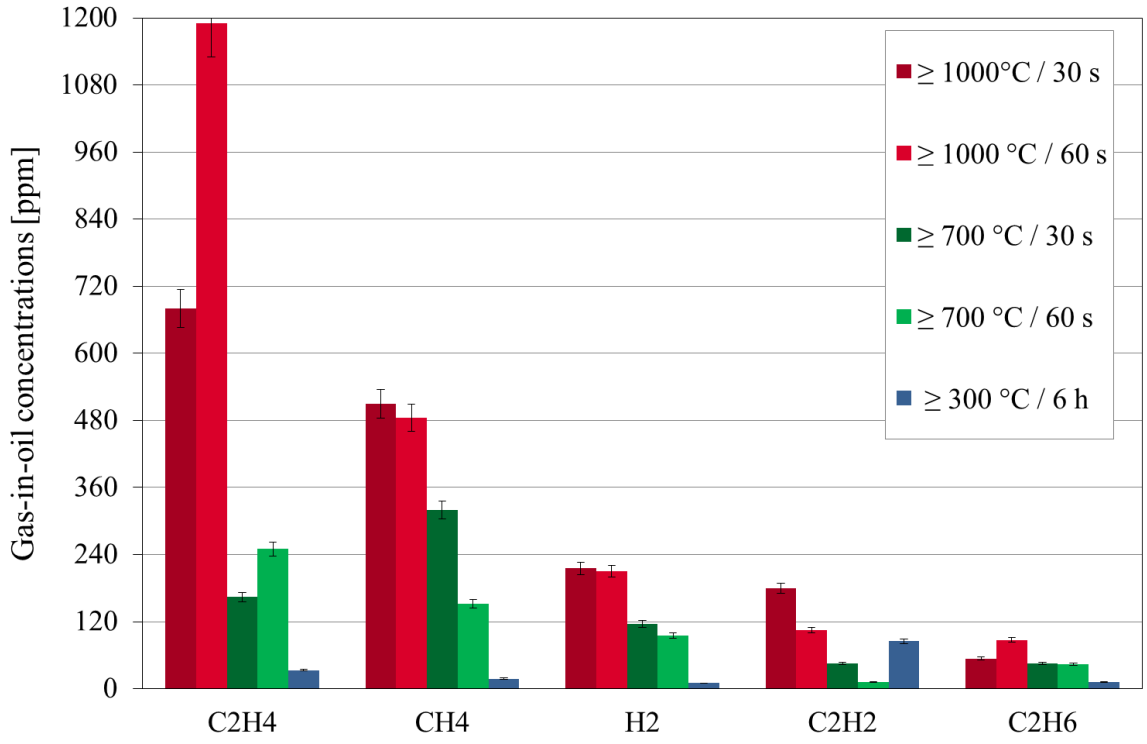

Figure 4.17: Maximum gas-in-oil concentrations measured after the hotspots

centrations measured after producing a hotspots of specific temperature. For hotspots of temperature 500 °C and above concentration of ethylene was the dominant gas, followed by concentrations of methane and hydrogen. Whilst, for the hotspots of 300 °C acetylene was the dominant followed by ethylene.

Figures 4.18 and 4.19 show the patterns of gas-in-oil concentrations obtained for the hotspots faults. It can be observed that the gas-in-oil concentrations for the hotspots of temperature 500 °C and above exhibit a very similar patterns, which can identified as a typical pattern for a thermal fault. However the hotspot at 300 °C exhibits a pattern of a fault-free condition of oil or, that of a slow developing thermal fault due to unusual generation of acetylene.

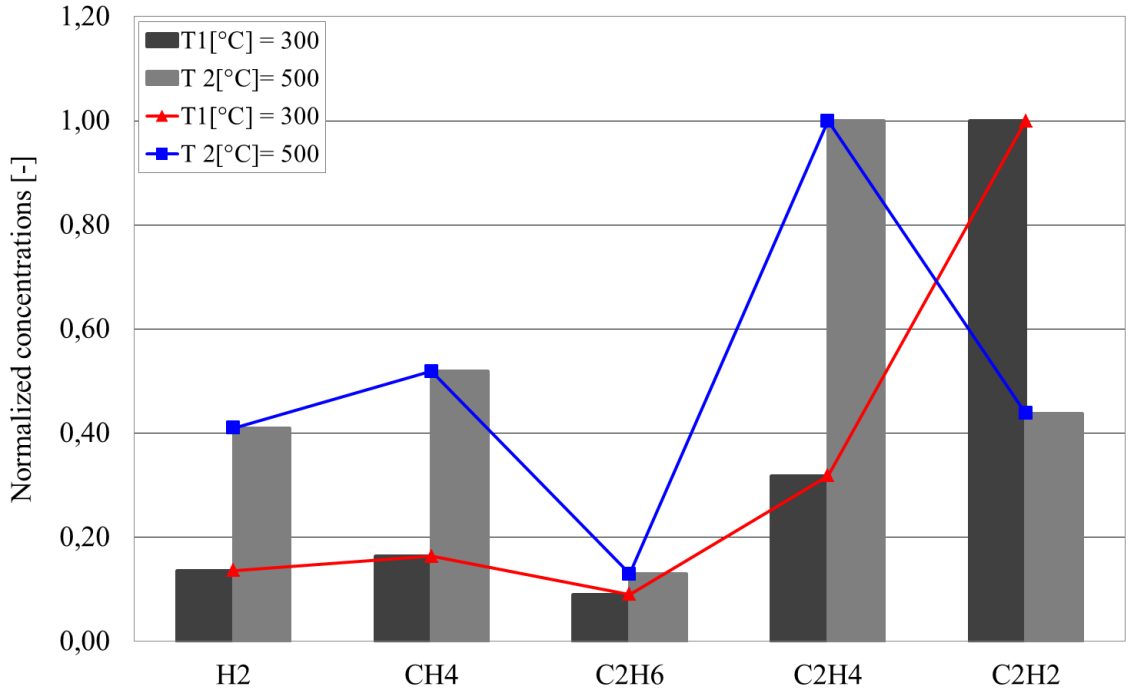

Figure 4.18: Gas concentration patterns obtained for hotspots of different temperatures

The fault diagnostic for hotspots was carried out by applying the CIGRE fault interpretation scheme, in order to verify the fault interpretations provided in the CIGRE scheme. The table 4.10 shows the comparison of the key ratios and threshold values obtained for the hotspot experiments with those (thermal faults) provided in the CIGRE scheme. Based on the both criterion of the CIGRE scheme (ratios and threshold) the hotspot fault of temperature 300 °C (HS-4), 500 °C (HS-3) and 1000 °C (HS-1) can be interpreted as arcing discharge fault, while hotspot fault of temperature 1000 °C can also be

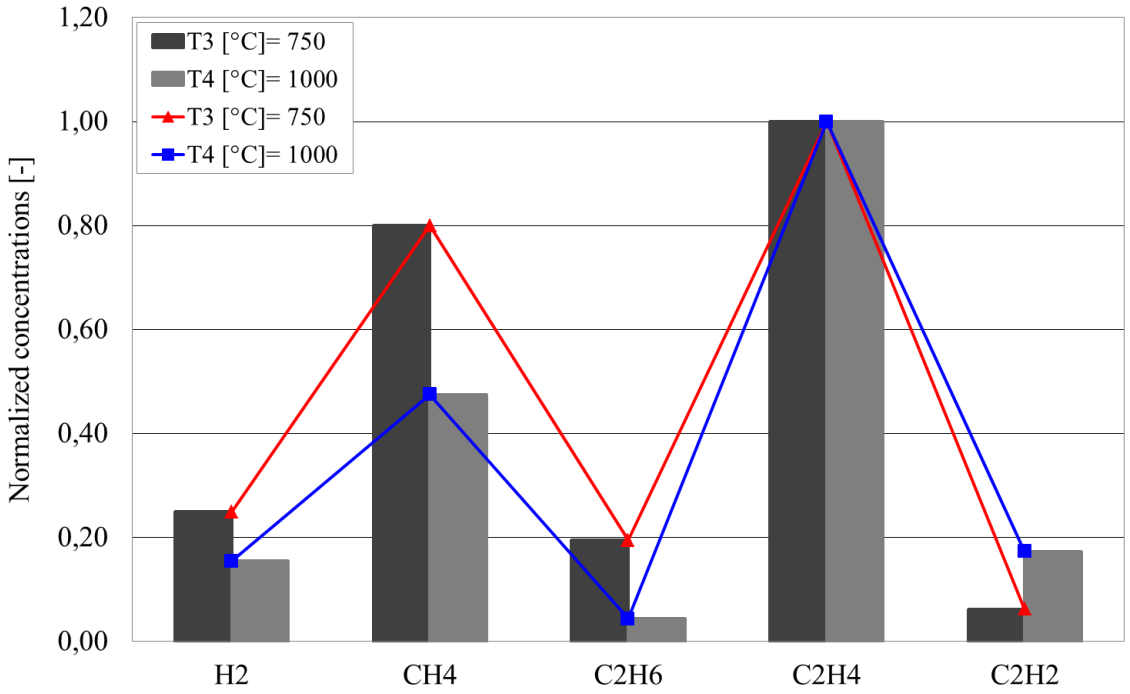

Figure 4.19: Gas concentration patterns obtained for hotspots of different temperatures

Table 4.10: Fault diagnostic by applying the CIGRE fault interpretation scheme (hotspot)

Key gas	CIGRE scheme		Hotspots			
Part I: Key gas ratios						
Key gas	**Ratio [-]**	**Fault type**	Ratio [-] **HS-1**	**HS-2**	**HS-3**	**HS-4**
(C_2H_2/C_2H_6)	> 1	AD	3.9	0.3	3.4	11
(H_2/CH_4)	> 10	PD	0.3	0.3	0.8	0.8
(C_2H_4/C_2H_6)	> 1	OH	22.6	5.1	7.71	3.5
Part II: Thresholds [ppm]						
Key gas	**Threshold [ppm]**	**Fault type**	Threshold [ppm] **HS-1**	**HS-2**	**HS-3**	**HS-4**
C_2H_2	> 20	AD	25	25	125	110
H_2	> 100	PD	189	100	177	15
$\sum C_xH_y$	> 1000	OH	173	595	823	2066
$\sum CO_x$	> 10000	CD	897	645	560	475

A D: arcing discharge, PD: partial discharge, OH: oil overheating, C D: cellulose degradation

confused as oil overheating. The hotspot fault of temperature 750 °C (HS-2) cannot be interpreted from the CIGRE scheme due to lack of sufficient crite-

ria. Thus, it can be suggested that the CIGRE scheme provides ambiguous interpretations of the hotspot faults.

4.2.3 Application of arcing discharge (AD)

Experimental Setup

This type of fault involves high amount of energy and it can result in severe failures of transformers. The simulation of arcing discharges under controlled parameters (voltage, current and duration time) was carried out in order to analyze gas-in-oil generation and gas behavior in oil induced due to arcing discharge fault. Very repetitive experiments were carried out under defined parameters in order to generate the faults of different intensities. In all cases the initial conditions of oil were maintained constant by means of oil reconditioning.

The results of these experiment were further used to investigate the process of diffusion of gases through oil before escaping to atmosphere via conservator tank.

The arcing discharge experiments were carried out using following equipments:

- Large scale setup system (see section 3.2)
- Oil treatment by VOT-3 system (see section 3.3.5)
- Transformer oil Nynas Nytro Lyra, new air saturated oil at normal ambient conditions (see table 3.2)
- DGA online monitoring system (see section 3.3.2)
- Current probe and oscilloscope

Methodology

All experiments were carried out with oil at normal ambient conditions. Previous to every experiment, the oil volume (approximately 600 litters) was reconditioned by means of several recirculation cycles between the main tank and VOT-3 system (see figure 3.4). Afterwards, the air saturation of oil was achieved by flow circulation between the main tank and conservator tank for approximately 12 hours. The table 4.11 displays concentrations of gases after oil reconditioning and air saturation.

Table 4.11: Gas-in-oil concentration after oil reconditioning and air saturation

	H_2	CH_4	C_2H_6	C_2H_2	C_2H_4	CO	N_2	O_2
Gas-in-oil [ppm]	5.0	1.0	12.0	10.0	5.0	9.3	57597	24407

Preliminary tests were conducted in order to define experimental conditions and parameters of the arcing discharge. Hence, the arcing discharge was achieved at approximately 380 V (primary voltage, U_1) and 95 kV (secondary voltage, U_2) for 30 seconds by means of an electrode needle-plate with a distance of 1 cm.

The transmission ratio of high voltage transformers(RHV) utilized in these experiments was approximately 380V:100000V, which was used for calculations of the current of the arcing discharge (or secondary current). The primary current was measured with aid of an oscilloscope.

The energy delivered by the arcing discharge can be estimated using equation 4.3.

$$E_{AD} = U_s \cdot I_s \cdot t \tag{4.3}$$

Where,
E_{AD} = total energy dissipated by the arcing discharge [kJ]
U_s = secondary voltage [kV]
I_s = secondary current [mA]
t = time period of fault application [s]

Immediately after conducting the arcing discharge faults in the oil tank, gas-in-oil concentrations were analyzed automatically at 1 hour interval at different sampling points (40, 90 and 160 cm) along the main tank (see figure 3.4). During the generation phase, the main tank was kept disconnected from the conservator tank, which remained closed until the gas-in-oil concentrations reached their maximum saturation in oil.

Results

The total energy dissipated during the three arcing discharge faults are presented in Table 4.12. Figure 4.20 shows the maximum concentrations of the selected gases measured during these experiments. It can be seen that hydrogen and acetylene are the dominant gases in all the cases. In the case of AD-3 the concentrations are slightly higher than that for the other cases, which can be associated with the higher amount energy dissipated during the experiment AD-3.

Table 4.12: Total energy dissipated during simulated arcing discharge (AD) faults

High voltage parameters	AD-1	AD-2	AD-3
Secondary current [mA]	156	160	164
Total energy [kJ]	456	456	467

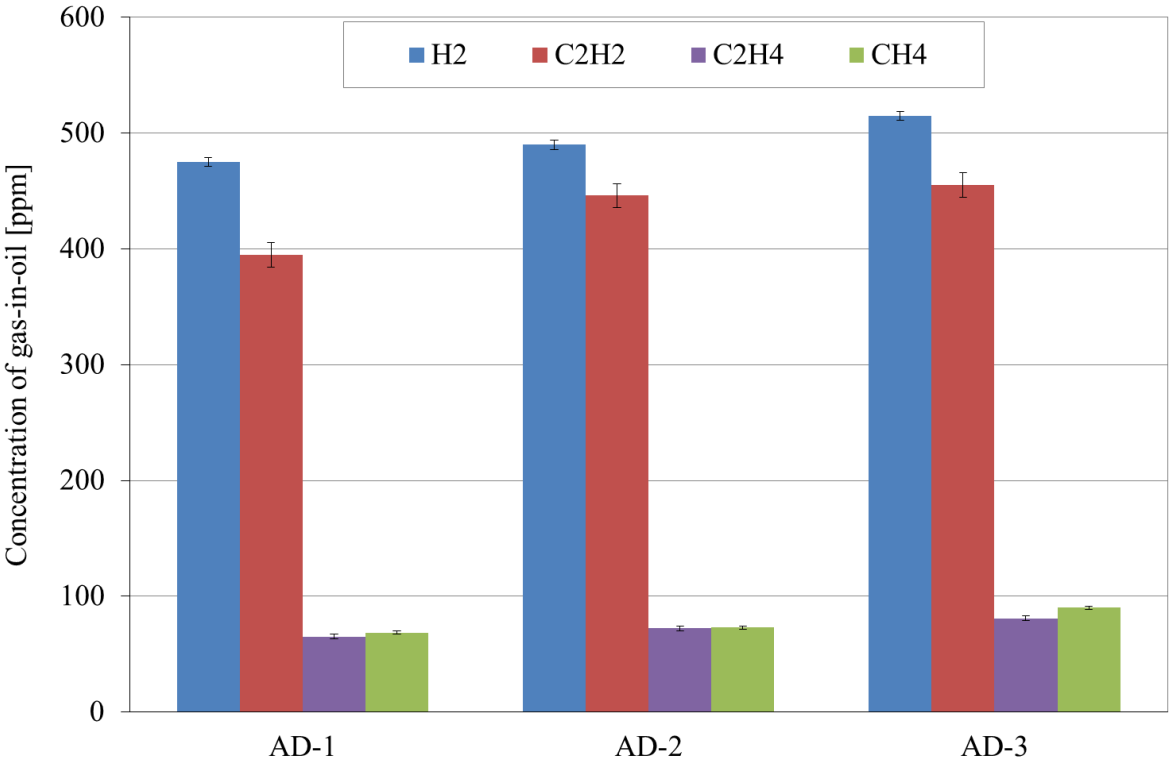

Figure 4.20: Maximum gas-in-oil concentrations generated during arcing discharge faults

The gas-in-oil concentrations obtained for the arcing discharge faults were also analyzed using the gas generation pattern method. In all the three arcing discharge experiments the gas concentrations were normalized on basis of concentrations of hydrogen. The figure 4.21 displays the graphical patterns of gas-in-oil concentrations. It can be observed that the resulting patterns for the arcing discharge experiments are very similar. Thus, it can be suggested that the arcing discharge faults can be represented by this typical pattern of the gas-in-oil concentrations.

The comparison of the CIGRE interpretation scheme (table 4.13) with the gas-in-oil concentrations obtained for the arcing discharge experiments shows that the key gas ratios and thresholds for all the three arcing discharge experiments indeed fit with the CIGRE criterion. From the CIGRE scheme the three faults can be interpreted as arcing discharge followed by overheating of the oil.

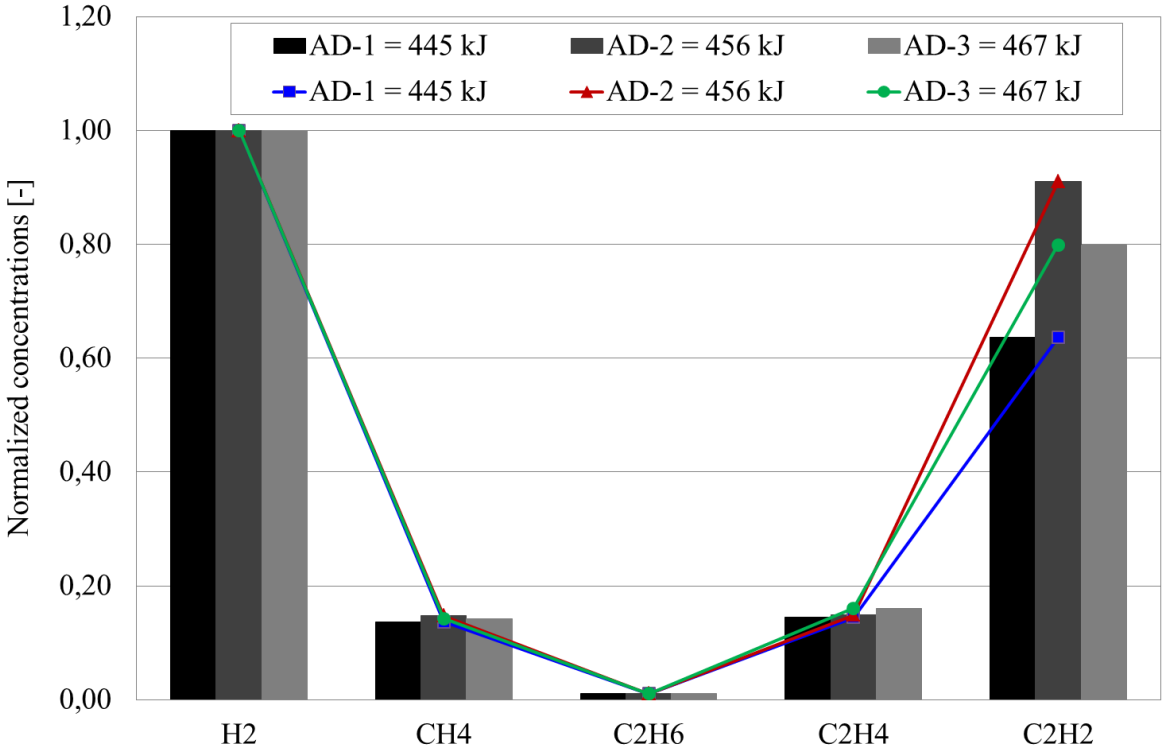

Figure 4.21: Gas concentration patterns obtained for the arcing discharge faults

Table 4.13: Fault diagnostic by applying the CIGRE fault interpretation scheme (arcing discharge)

Key gas	CIGRE scheme		Arcing discharge		
Part I: Key gas ratios					
Key gas	**Ratio [-]**	**Fault type**	Ratio [-] **AD-1**	**AD-2**	**AD-3**
(C_2H_2/C_2H_6)	> 1	AD	79.0	89.2	87.1
(H_2/CH_4)	> 10	PD	7.3	7.0	6.4
(C_2H_4/C_2H_6)	> 1	OH	13.8	13.8	18.1
Part II: Thresholds [ppm]					
Key gas	**Thrsh. [ppm] [ppm]**	**Fault type type**	Threshold [ppm] **AD-1**	**AD-2**	**AD-3**
C_2H_2	> 20	AD	395	446	455
H_2	> 100	PD	475	490	515
$\sum C_xH_y$	> 1000	OH	1003	1081	1140
$\sum CO_x$	> 10000	CD	150	148	156

A D: arcing discharge, PD: partial discharge, OH: oil overheating, C D: cellulose degradation

Hence, the CIGRE scheme indicates that these faults occurred certainly as arcing discharge of high energy which produced oil overheating. Though partial discharge could be also included in this fault interpretation it is discarded due to indication the key gas ratio.

4.2.4 Diffusion of fault gases from oil to atmosphere

The mass transfer of gases from oil to atmosphere often affects the results of DGA analysis. The mass transfer occurs in the open-breathing conservator tank due to diffusion of gases from oil into the surrounding air. Therefore, the diffusive (from oil to air) behavior of gases generated in oil during arcing discharge faults was investigated in order to determine the rate of mass transfer of fault gases from the oil balance to the atmosphere.

Based on measurements of gas-in-oil concentrations taken at three different locations (depth) inside the oil tank, it was possible to establish the gas concentration profile during the gas generation as well as the gas diffusion. The identical values of gas-in-oil concentrations at all locations implies that the gas concentrations are uniform within the oil balance. These uniform gas-in-oil concentrations were typically followed by a progressive decrease in the concentrations due to diffusion of gases from oil to the atmosphere through the oil-air interface inside the 'open-breathing' conservator tank.

Methodology

In order study the diffusion of the gases from oil to atmosphere four different arcing discharge experiments were conducted under identical conditions as those of the three arcing discharge experiments mentioned in the previous section 4.2.3. However, these experiments differ with respect to the rate of oil circulation (mixing) inside the oil tank during the generation and diffusion of fault gases. Table 4.14 presents the experiment number with its corresponding oil pump rate.

Table 4.14: Oil pump rate for arcing discharge experiments

Arcing discharge Experiment No.	AD-4	AD-5	AD-6	AD-7
Rate of oil circulation [l/min]	3.0	1.5	1.0	0

Right after applying the arcing discharge in the oil tank, gas-in-oil concentrations were monitored by DGA online system at 1 hour intervals. The sampling points were located along a vertical distance at 40 cm, 60 cm and 160

cm measured from the tank cover (figure 3.4). The continuous monitoring of gas-in-oil concentrations at the specific locations provided concentration-time profiles which allowed to identify gas generation phase and diffusion phase.

During the phase of gas generation the main tank remained closed and disconnected from the conservator tank. This condition was maintained until the gas concentrations reached their maximum saturation levels in oil and quasi-homogeneous concentration in the whole oil volume. In the second phase the main tank was connected to the conservator. In this phase a progressive decrease of gas-in-oil concentrations occurs as a result of diffusion of gases from the oil balance to the atmosphere.

Results

Figure 4.22 shows the concentration-time profile for hydrogen generated in the oil balance at different depths for experiment AD-7 (no oil circulation). The plot demonstrate that during the entire generation phase the hydrogen concentration is non-homogeneous within the oil balance. The concentration

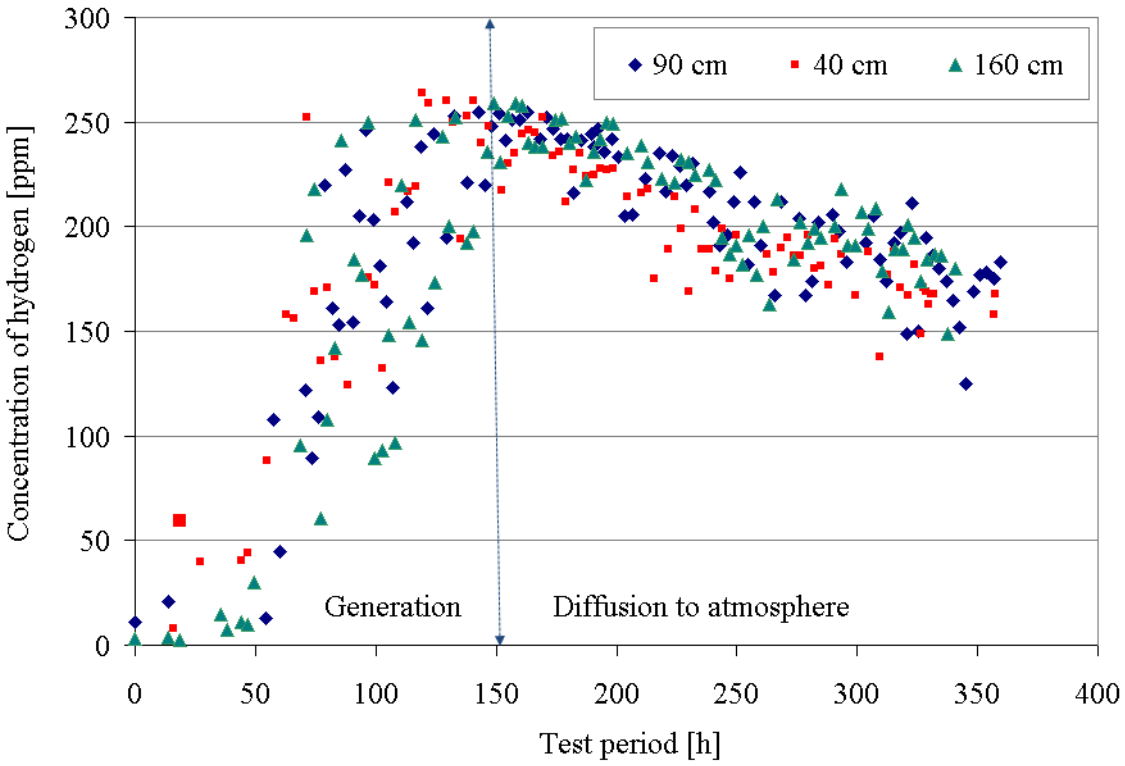

Figure 4.22: Gas-in-oil concentration profile at different locations in the oil balance (with zero oil circulation)

tends to be homogeneous just after the peak concentration of approximately 250 ppm (at 150 hours) is surpassed. However, in the diffusion phase the concentration tends to be non-homogeneous again which can be attributed to a non-uniform diffusion process within the oil. The other gases generated during the fault also exhibited similar tendencies.

Figure 4.23 shows the concentration-time plot for hydrogen generated in the oil balance at different depths for experiment AD-4 (circulation rate of 3 l/min). It can be seen that because of the oil circulation, the gas concentrations in the whole oil balance became homogeneous right at the beginning of the generation phase. The maximum concentration of hydrogen (approximately 850 ppm) was reached at 24 hours. Further, the concentration decreases almost linearly due to the diffusion of hydrogen from oil to air.

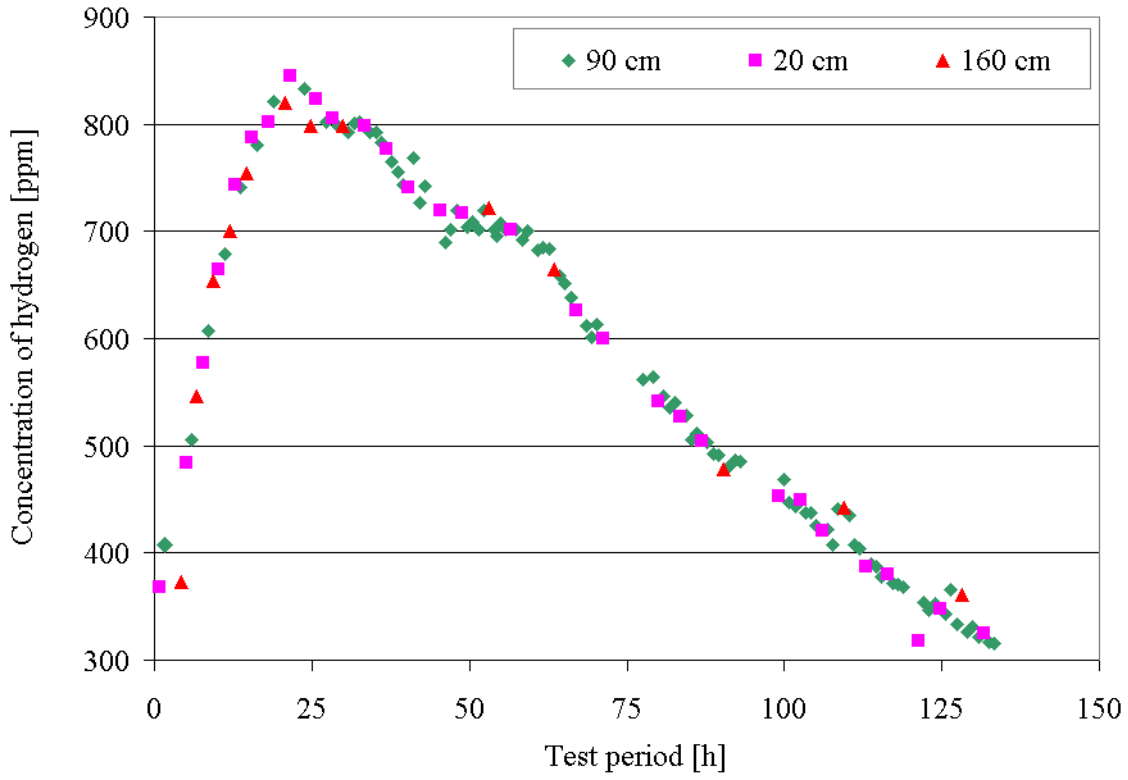

Figure 4.23: Gas-in-oil concentration profile at different locations in the oil balance with oil pump circulation 3 l/min

The diffusion or mass transfer rate of gases diffusing from the oil balance to atmosphere can be associated with the mass transfer coefficient (K_{OL}). The

mass transfer coefficient represents a transfer rate of a gas concentration diffusing from a liquid surface exposed to the atmosphere, as it occurs in the conservator tank.

The mass balance of a fault gas-in-oil diffusing into the atmosphere can be expressed as equation 4.4 [Guo et al., 2002].

$$\frac{dW_L}{dt} = -A \cdot K_{OL} \cdot \left(C_L - \frac{C_G}{H} \right) \tag{4.4}$$

Where,
$\frac{dW_L}{dt}$ = Mass gradient of fault gas [g/h]
A = surface area of diffusion in the conservator tank [m^2]
K_{OL} = overall mass transfer coefficient in the liquid phase [m/h]
C_L = concentration of fault gas in the oil [$\mu g/m^3$]
C_G = concentration of fault gas in the air [$\mu g/m^3$]
H = Henry's constant [$\mu g/m^3$]

The overall mass transfer coefficient of gases dissolved in oil (K_{OL}) was determined by means of non-linear regression fitting of time-concentration data obtained in each experiment of gas generation. This statistical method allowed to model the experimental data by a nonlinear diffusion function based on a combination of different independent variables. The procedure was applied to obtain the mass transfer coefficient of critical fault gases such as hydrogen, acetylene, and methane, which are produced at the highest concentrations.

In order to plot the time-concentration curve for the diffusion phase, the maximum concentrations (saturation concentration) were assumed to be the initial concentrations at start of the diffusion phase. The concentration of the fault gases in the air was assumed to be zero due to their infinite dilution. The fitting curve (MT_{ca}) obtained for the diffusion phase of hydrogen at an oil pump rate of 3 l/min is presented in figure 4.24. The results for the overall mass transfer coefficients ($K_{OL(i)}$) of the key fault gases i, are summarized in table 4.15.

The diffusive flux of these gases was determined according to the gradient flux law which states that the diffusive flux of a given component is a function of its concentration gradient and mass transfer rate, see equation 4.5 [Scott et. al, 2002].

$$F_{OL(i)} = K_{OL(i)} \times (C_L - C_G) \tag{4.5}$$

Where, $F_{OL(i)}$ = diffusive flux of the gas i [mg/(h m^2)]

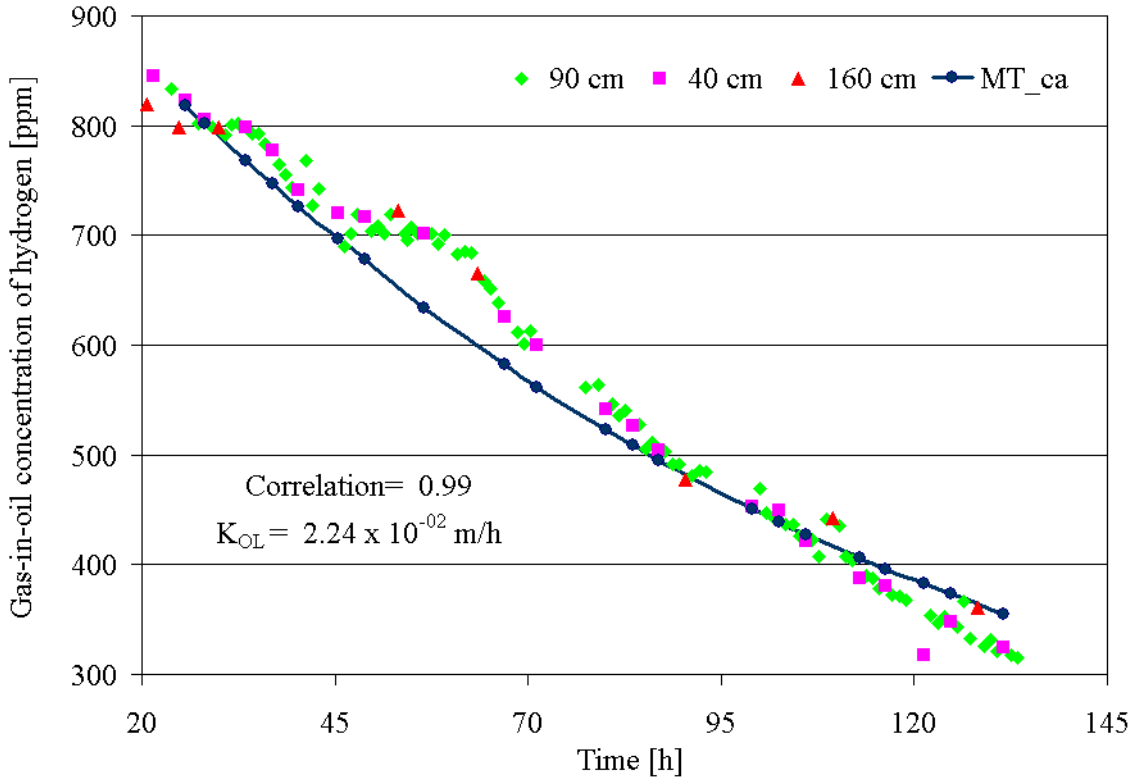

Figure 4.24: Estimation of mass transfer coefficient (K_{OL}) for hydrogen (oil pump rate: 3 l/min)

Table 4.15: Overall mass transfer coefficients ($K_{OL(i)}$, $[m/s]$) of fault gases

	oil pump rate [l/min]			
	3.0	1.5	1.0	0
H_2	2.4 x 10^{-2}	2.1 x 10^{-2}	1.9 x 10^{-2}	6.9 x 10^{-3}
C_2H_2	2.3 x 10^{-3}	3.1 x 10^{-3}	1.3 x 10^{-3}	4.2 x 10^{-4}
CH_4	2.1 x 10^{-2}	3.2 x 10^{-2}	1.8 x 10^{-2}	1.9 x 10^{-3}

The diffusive flux of the investigated fault gases for different oil pump rates is presented in figure 4.25. It can be observed that the diffusion rate of the gases increases as the the oil pump rate is higher. Irrespective of the oil pump rates, the diffusion flux of hydrogen is always higher than the diffusion flux of other gases, followed by the fluxes of methane and acetylene. These ranks of diffusive fluxes also comply with the solubility of these gases in oil at normal ambient conditions.

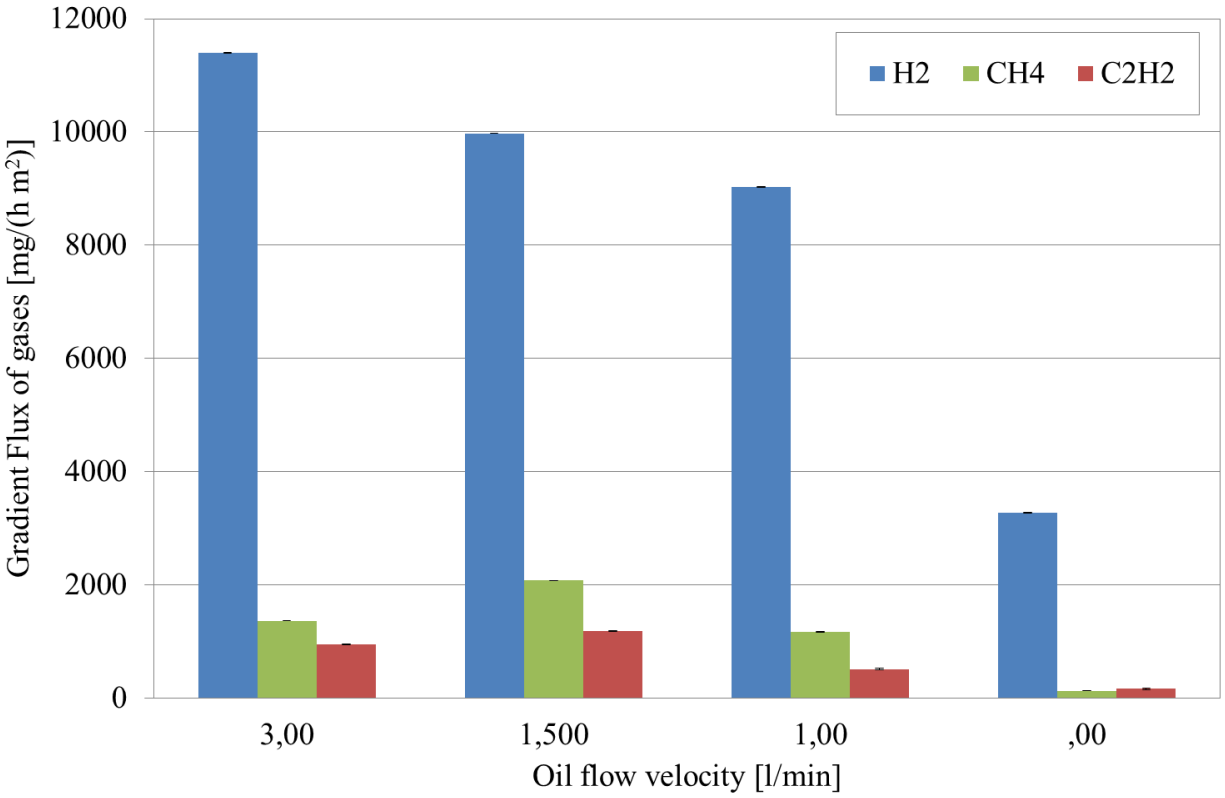

Figure 4.25: Diffusion flux of fault gases escaping the transformer oil for different oil pump rates

5 Summary and Outlook

5.1 Summary

Efficient and safe functioning of a transformer requires effective and timely assessment of its condition. A very dangerous condition of the transformer arise from the fault gas generation as a result of incipient faults and aging of the insulation materials. Application of the dissolved gas analysis (DGA) method has been widely recognized as a useful technique to assess fault conditions of a transformer. The transformer oil is a vital information carrier that provides insight into any malfunctioning of a transformer and it allows to apply timely any the most suitable corrective measurement. However, an effective gas-in-oil analysis is essential and its effectiveness is subjected to the adequate conduction of the DGA method.

Since about four decades, the DGA method has being gaining great attention as one of the most efficient and convenient methods for fault diagnostic in transformers. Thus, power agencies has joined forces with the oil diagnostic field in order to develop advanced measurement techniques for gas-in-oil analysis, as well as to improve statistical interpretation schemes used for the fault diagnostic.

The main objective of this research project was to evaluate the factors affecting the results of DGA method including the commercially available gas-in-oil measurement techniques. Additionally, this work focused on investigating the generation of fault gases by subjecting transformer oil to typical electrical and thermal faults as they occurred in transformers and verifying those faults by means of the DGA method. The knowledge acquired from these experimental investigations is deemed to contribute at a reliable fault interpretation and diagnostic according to the DGA method.

An extensive part of this research work was focused on designing and constructing experimental setups to conduct simulations of thermal and electrical faults as they occur in power transformers. The construction of a small scale setup (30 kV and 12 liter oil tank) and a large scale setup (100 kV and 600 liter oil tank) including oil tanks, oil circulation system, high voltage system, and control panel was accomplished with necessary details.

The small scale setup, consisting of a 12 liter test vessel and a high voltage supply system of 30 kV, was used to simulate partial discharges fault and hotspots of different temperatures. Experiments carried out in the small test setup were aimed at gaining insight about the fault gas generation process occurring in transformer oil when the oil is subjected to electrical or thermal stresses of different intensities. Moreover, this setup was also useful at evaluating the generation of gas-in-oil and measurement efficiency of various commercially available DGA techniques.

The design of the large scale experimental setup provided an enhanced model of an air-breathing power transformer and its oil circulation system. This large scale setup allowed investigations by subjecting a larger volume of oil (600 liter) to electrical stresses such as arcing discharges of high intensity. The oil circulation system controlled by an automated system allowed to conduct mixing or regeneration of the whole oil volume, resembling the slow flow rate of oil in a power transformer for cooling purpose. This setup was used to investigate the fault gas generation in oil due to high intensity arcing discharge faults. The diffusion flux of gases from oil to atmosphere via conservator tank of a transformer was also investigated by means of this setup.

Factors affecting the dissolved gas analysis (DGA)

Gas extraction techniques: Most of the gas-in-oil monitoring techniques cannot measured dissolved gases before extracting them from the oil, which is a very critical step of the DGA method. The dissolved gases need to be first efficiently extracted from the oil sample before feeding them to a gas analyzer, such as a gas chromatograph. Consequently, the efficiency of the extraction techniques has direct influence on the reliable quantification of dissolved gases and thus a proper fault diagnostic with the DGA method.

Four different gas extraction techniques: vacuum extraction (VE), shaking syringe (SS), equilibrium head space (EHS) and dynamic head space (DHS) were tested during these investigations. For that purpose, concentrations of critical fault gases: hydrogen, acetylene, ethylene and methane in multiple oil samples from the same oil batch were analyzed. The concentrations of the fault gases extracted from the samples using the vacuum extraction (VE), shaking syringe (SS), equilibrium head space (EHS) were measured using the same gas chromatograph (Mobil GC, Energy Support) under similar calibration parameters, however the gases extracted by dynamic head space (DHS) were analyzed by its integrated photo-acoustic mass spectrometer. The efficiency and the consistency of these techniques were evaluated in terms of precision and standard deviations of the measurements.

The analysis revealed that the measurements using gas extraction technique VE (both online and manual modes) leads to the highest concentrations of gases, which implies that VE technique has the highest efficiency to extract gases, followed by EHS and DHS techniques which also lead to relatively high gas concentrations. However, concentrations achieved by the manual extraction method, using SS, demonstrated the lowest efficiency for gas extraction. This fact is attributed to the manual generation of the vacuum extraction and several man induced deviations involved in the conduction of the gas extraction. The evaluation of relative standard deviations (RSTD) of the measurements suggests that EHS technique has the highest consistency ($RSTD < 2.1\%$) of achieving gas extraction from oil sample. VE technique also achieves sufficiently high consistency. On the other hand, SS and DHS techniques are relatively inconsistent ($RSTD > 5\%$) in performing gas extraction.

The DGA systems with VE technique is designed to carry out automatic online monitoring, therefore it is very convenient for continuous measurements. However, it needs frequent calibrations due to certain technical instability. The portable DGA system (Kelman Transport X) based on DHS technique and photo-acoustic spectroscopy is easy to carry and operate for on site manual gas-in-oil measurements. The DGA with SS technique needs manual gas extraction using a costumized syringe and manual shaking, therefore the consistency and the accuracy of the results is highly subjected to man induced errors.

Sampling and storage of oil: Dissolved gas analysis should be carried out according to the method proposed in the international standards guidelines IEC 60567 [IEC 60567, 2005]. However these guidelines are sometimes neglected in the practice, which often leads to exposure of oil sample to air-trapping, light, high temperature and prolonged storage duration, consequently affecting the quality of DGA results and fault diagnostics.

Air bubbles trapped in an oil sample lead to escape of gases dissolved in the oil through diffusion of the gases into the air bubble, thus decreasing the actual gas-in-oil concentrations. For less soluble gases the decrease in concentration is higher due to faster diffusion process. The experimental results showed that the decrease in gas-in-oil concentration is significant for air bubbles of volume more than 2 % of the sample volume. Air bubbles occupying approximately 8 % of the sample volume can cause decrease in concentration by approximately 30 % for hydrogen, 15 % for methane and 35 % for carbon monoxide. These deviations are higher enough to cause false interpretation of a pattern of dissolved gases and subsequent fault diagnostic.

Light exposure and temperature variations of oil samples can directly influence oxidation reactions in the oil. Exposure to sunlight can trigger photochemical oxidation reactions among hydrocarbon molecules and decomposition products, which create further generation of molecular hydrogen. An exposure to daylight for 8 days at normal ambient conditions causes up to 18 % increase in the concentration of hydrogen.

The oil samples stored at 7 °C, 18 °C and 60 °C revealed that at the temperature of 18 °C or below does not cause significant changes in gas-in-oil concentrations, however temperature up to 60 °C causes increase in the concentrations by 12.5 % for hydrogen and 45 for ethane. Thus, it was demonstrated, why an oil sample must be stored in dark and at below-room temperature.

The investigations on storage duration revealed that an adequate storage of oil samples up to 16 days does not lead to any significant changes in gas-in-oil concentrations.

Stray gassing behavior: Some types of transformer oils, when they are exposed to copper windings in transformer at temperature above 60 °C, exhibit abrupt increase in concentrations of hydrogen and methane. This behavior was demonstrated though experiments that confirmed the stray gassing tendency of non-inhibited oils such as Nynas Nytro 10GBN. Based on this results, it is recommended to consider a possible stray gassing behavior of an oil during any fault interpretations by DGA.

Gas-in-oil generation due to faults

The partial discharge (PD) faults were generated in the small scale setup. Since partial discharge is a very instable phenomenon, after carrying out numerous attempts only two consistent PD events of duration 58 hours and 115 hours, at a mean apparent charge of 1000 pC were achieved. The statistical assessment of total number of instantaneous discharges during the PD events, required for estimation of total fault energy, was not possible due to technical limitations. Nonetheless, the PD events were assessed on the basis of phase resolved partial discharge (PRPD). The PD event of 58 hour duration occurred with high pulse frequency and mean voltage of 11 kV. The PD event of 115 hour occurred with low pulse frequency and mean voltage of 19 kV, it was characterized by an arcing discharge fault at the end.

The PD fault of 58 hour duration led to gas-in-oil concentration of 172 ppm for hydrogen, followed by 9.6 ppm for methane. It was observed that such pure PD event occur at temperatures below 150 °C and low current level, thus it behaves like a low intensity fault with slow generation of fault gases.

The PD fault of 115 hour duration produced gas-in-oil concentration of 905 ppm for hydrogen, followed by 304 ppm for acetylene. The patterns of gas concentrations demonstrated that the gas generation process occurred during these two faults may have been different from each other.

Furthermore, the assessment of the gas generation process using gas generation pattern method (see section 2.14) suggests that the PD event of 58 hour duration is indeed a partial discharge fault while the PD event of 115 hour duration may have been combined with an arcing discharge fault. Thus, it was demonstrated that partial discharge faults can be detected and distinguished using gas generation patterns. On the other hand, the interpretation of the gas-in-oil concentration using CIGRE fault interpretation scheme led to uncertain diagnostics of the PD event of 115 hour duration.

The hotspot (HS) faults were investigated using the small test setup, the hotspots were achieved by powering a semi-conductor material (graphite pencil lead) at different current levels. Due to technical limitations it was impossible to measure the actual oil temperature near a hotspot. Therefore the temperature was estimated as a function of time, current, voltage and resistance of the semi-conductor material. Thus, it was possible to achieve hotspots of temperatures approximately 300 °C, 750 °C, 500 °C and 1000 °C by controlling the current, voltage and resistance.

The energy produced due to thermal stress in oil leads to decomposition of hydrocarbon molecules, evolving gases such as ethylene, methane, hydrogen and acetylene in higher concentrations. From the obtained experimental data it was observed that the gas-in-oil concentrations produced due the thermal faults do not increase linearly with energy dissipated by the fault.

The assessment of the thermal faults using gas generation pattern method indicates that the hotspots of above 500 °C temperature are represented by an identical gas generation pattern, which is identified as a typical gas generation pattern for a thermal fault. This pattern is characterized by the concentration of ethylene being highest among all the critical gases. On the other hand, thermal fault at 300 °C was characterized by the concentration of acetylene being highest, which is associated with slow oil overheating. The gas generation pattern produced by this fault indicates an incipient fault evolving slowly and unnoticeable to become a threatening overheating fault.

The assessment of the hotspots of 300 °C, 500 °C and 1000 °C using CIGRE fault interpretation scheme lead to misinterpretation of the fault as arcing discharge faults, while the hotspot 750 °C could not be interpreted due to lack of sufficient criteria. This is caused due to limitations of the CIGRE scheme

to distinguish the fault on the basis of its dissipated energy. However, the gas generation patterns obtained for the hotspots show that a reliable diagnostic of these faults can be achieved using the typical gas generation pattern.

The arcing discharge (AD) fault was investigated using the large scale setup. Three discharge fault experiments were conducted by applying primary voltage of 380 V and secondary voltage of 95 kV to needle-plate electrodes located in the oil tank. During the experiments large concentrations of hydrogen and acetylene, along with minor quantities of ethylene and methane were generated due to breakdown of hydrocarbon molecules under high intensity current and temperature of the arcing discharge fault.

The assessment of the arcing discharge faults using gas generation pattern method showed that the three faults produce very similar gas generation pattern. This pattern can be recognized as a typical gas generation pattern for arcing discharge faults. The CIGRE fault interpretation scheme also provided a coherent interpretation of the faults as arcing discharge faults with subsequent oil overheating due to high amount of dissipated energy.

Diffusion of fault gases to atmosphere

Diffusion of fault gases to atmosphere via conservator is one of the most critical factor that can cause deviations in DGA. The diffusion of the gases can result in reduced gas-in-oil concentrations, consequently leading to false interpretation of the faults.The investigations were focused on the diffusion flux of the three critical fault gases: hydrogen, methane and acetylene. These gases were chosen because they are usually found in largest concentrations in oil, as well as they are distinguished by their solubility in oil. Four different experiments were conducted using different oil circulation rates. The concentrations of the gases were monitored for a certain period after the conductions of the faults. The mass transfer coefficients for the gases were obtained from the concentration-time profiles and the corresponding diffusion flux was estimated using the gradient flux law.

Highest diffusion flux was obtained for hydrogen, followed by methane and then acetylene, which implies that the diffusion flux depends on the solubility of the gas. Furthermore, it was demonstrated that the diffusion flux of gases is strongly dependent on the rate of oil circulation between the main tank and the conservator, higher the circulation rate stronger the diffusion flux of the gases.

The strong diffusion flux of hydrogen can result in significant reduction of its concentrations in oil in a short time. Since hydrogen is a critical gas for

indication of an electrical fault in a transformer, a reduction in its concentration due to diffusion flux can lead to underestimation of a severe electrical fault. Similarly, high oil circulation rate can also lead to false DGA and fault diagnostics. Therefore, it is strongly recommended to take in to account the diffusion flux of the gases and the oil circulation rate the transformer while carrying out fault diagnostic using DGA.

Following conclusion can be outlined based on results and knowledge gained though these experimental investigations:

- The technique of gas-in-oil extraction of the DGA method has direct and significant influence in the accurate assessment of gas-in-oil concentrations. The gas extraction by vacuum degassing (VE) resulted to be the most efficient technique to extract dissolved gases. In both modes, automatic online as well as manual, exhibited the highest efficiency and precision of the quantification of gas concentrations. Special attention should be given to manual gas extraction techniques, such as shaking syringe (SS), which proved to have poor efficiency and consistency to quantify dissolved gases in oil.

- The factors related to sampling and storage of oil samples, namely air-trapping, light exposure and temperature, have significant influence on gas-in-oil concentrations. Therefore extreme care should be taken in regard with the procedures of oil sampling and storage of samples. However, samples stored under adequate conditions can guarantee reliable measurements of gas-in-oil concentrations up to 16 days.

- Similarly, in case of some types of oils, stray-gassing behavior can be major factor to influence DGA. Therefore stray-gassing behavior of such oils must be accounted for while carrying out a fault diagnostic by DGA, since increased hydrogen concentrations can be mistaken as fault gases corresponding to a partial discharge.

- Partial discharge faults are a low intensity faults which occur at low temperatures, however in some cases they can be accompanied by arcing discharges producing large concentrations of hydrogen, methane and acetylene. The thermal faults due to hotspots above 500 °C generate ethylene, methane, hydrogen and acetylene in large amounts. The amount of generated gases increases rapidly for temperatures above 1000 °C. Arcing discharge faults involve much higher amount of energy dissipation, producing the largest concentrations of hydrogen and acetylene.

- The fault interpretation scheme proposed by CIGRE TF 15.01.01, which is one of the latest DGA interpretation schemes, provided uncertainty

at the diagnostic of experimental faults such as partial discharge faults and hotspots. On the other hand, it proved to be consistent at the diagnostics of experimental arcing discharge faults. However, based on the overall results it may be concluded that the CIGRE scheme should be applied cautiously and other factors must be considered for a reliable diagnostics.

- The graphic DGA interpretation method of gas generation pattern resulted to be sufficiently reliable at the diagnostics of experimental faults partial discharge (PD), hotspot (HS) as well as arcing discharge (AD) faults. This method exhibits strong potential to be utilized for fault diagnostics as a separate method or in combination with the interpretation scheme proposed by CIGRE TF 15.01.01.

- Investigation on the diffusion flux of gases escaping to atmosphere via conservator confirmed that the diffusion has strong influence on fault diagnostic by DGA. Reduction in the gas-in-oil concentrations due to the diffusive flux can lead to inaccurate quantification of fault gas generation in the oil balance and consequently incorrect fault diagnostics. Diffusion flux resulted to be the highest for hydrogen due to its relative lower solubility in the gas mix, however the diffusion flux of gases tends to increase at higher oil circulation rates.

5.2 Outlook

Based on the experience gained during these investigations, following suggestions can be pointed out for future research work and practical application of DGA.

- For the further investigations related to the fault gas generation and their evaluation by DGA, it is recommended to add other factors affecting the gas generation process, such as the presence of insulation paper, fluctuation of transformer voltage load and oil temperature.

- Studies to gain knowledge about the chemical composition of transformer oil can aim at better understanding the process of oil oxidation under the effect of faults. A more detailed characterization of the hydrocarbon types of transformer oil can be achieved by analysis with supercritical fluid chromatography (SFC) combined with mass spectroscopy [Drews, 1998].

- The present fault interpretation schemes do not provide any information regarding the intensity of the fault. Experiments should be carried out to obtain extensive data regarding fault intensity (or fault energy)

and gas-in-oil concentrations. This data should be used to establish correlation between the fault intensity and the gas-in-oil concentrations. This correlation can be then used in a fault interpretation scheme to enhance the fault diagnostic on the basis of dissipated energy.

- Slowly developing faults do not become evident by intermittent DGA measurements, which lead to dangerous conditions without being noticed. Long term and continuous DGA monitoring of oil in service transformer could allow better understanding of slowly developing faults.

- The physical relationship between gas-in-oil concentrations and technical condition of a transformer cannot be described mathematically, however it can be incorporated into a computer model using fuzzy rules based on practical experience and experimental observations. An improvement of the CIGRE interpretation scheme was proposed by Aragón et. al. (2007) by implementing the fuzzy inference system (FIS). Thus deficiencies of the CIGRE interpretation scheme were eliminated by merging the two criteria (key ratios and thresholds) into one well integrated set of fuzzy rules, substituting the threshold by steady membership functions, and estimating the likelihood of fault. Further work related to the FIS can be found in Fischer and Tenbohlen (2009).

List of Symbols and Abbreviations

List of Symbols

ΔE	Activation energy of the reaction, in J/mol
$\Delta G_{m,mix}$	Change in Gibbs free energy per mole of solution
μ_i^*	Chemical potential of pure liquid 'i'
Φ	Magnetic flux through one turn of winding
A_k	Reaction constant according to kinetics
A	Surface area of diffusion, in m^2
$C_{C(i)}$	Concentration gradient of the fault gas in the conservator tank
$C_{D(i)}$	Concentration of the gas diffused to the atmosphere, in mol/l or $\mu g/m^3$
C_{gas}	Concentration of the gas in the gas phase, in mol/l or $\mu g/m^3$
C_{liq}	Concentration of gas in liquid phase, in mol/l or $\mu g/m^3$
C_A	Aromatic percentage in transformer oil
c_H	Henry's dimensionless constant
C_N	Percentage naphthenic structures n transformer oil
C_P	Percentage paraffinic structures in transformer oil
D	Diffusion coefficient, in m^2/s
E_{AD}	Total energy dissipated by the arcing discharge, in kJ
F_{OLi}	Diffusive flux of the gas i, in $mg/(hm^2)$
FR	Specific pump flow rate for oil circulation aimed at mixing of oil
H	Henry's constant, in $\mu g/m^3$
I_p	Primary current, in mA
I_s	Secondary current, in mA
J	Diffusion flux, in $mol/m^2.s$
K_{gas}	Liquid phase mass transfer coefficient, in m/h
K_{liq}	Liquid phase mass transfer coefficient, in m/h
K_{OL}	Overall mass transfer coefficient in the liquid phase, in m/h
k_H	Henry's temperature-dependent constant, in atm/mol
N_p	Number of turns of the primary winding

N_s	Number of turns of the secondary winding
Q_{IEC}	Mean apparent charge of partial discharge
P_{gas}	Partial pressure, in atm
P_i	Vapor pressure of a component i
P_i^*	Vapor pressure in pure state
PAC	Poly-aromatic components percentage in transfomer oil
R	Universal gas constant
T	Absolute temperature, in K
t	Time period of fault application, in s
U_s	Secondary voltage, in kV
$V_{C(i)}$	Volumetric flow of the fault gas is transferred to the conservator, in l/min
V_{gas}	Volume of the gas in the gas phase, in l
V_{liq}	Volume of the gas in the liquid phase, in l
$V_{T(i)}$	Volume of a fault gas 'i' dissolved in oil, in l
V_p	Instantaneous primary voltage, in kV
V_s	Instantaneous secondary voltage, in kV
x_i	Mole fraction of component 'i'

List of Abbreviations

AC	Alternating current
DC	Direct current
HV	High voltage
PD	Partial discharge fault
AD	Arcing discharge fault
HS	Hotspot fault
OH	Oil overheating fault
CD	Cellulose degradation fault
FR	Oil flow rate
ASTM	American Society for Testing and Materials
IEC	International Electro-technical Commission
CIGRE	Conseil international des grands réseaux électriques (The International Council on Large Electric Systems)
TF	Taks Force of CIGRE
DGA	Dissolved gas analysis
VE	Vacuum extraction
SS	Shaking syringe
EHS	Equilibrium head space
DHS	Dynamic head space
RSTD	Relative standard deviations
MODBUS	Automation application for communication between devices and data exchange

PAS	Photo-acoustic spectroscopy
Mobil GC	Mobile gas chromatography
TCD	Thermal conductivity detector
FID	Flame ionization detector
NIS	Natural internal standard
TGM	Transformer gas monitoring
VOT	Variable oil treatment
PRPD	Phase resolved partial discharge
PAC	Polyaromatic compunds

References

Acheson, 1990: Acheson, D. J., 1990. *Elementary Fluid Dynamics*. Oxford Applied Mathematics and Computing Science Series, Clarendon Press, England.

Altmann, 2004: J. Altmann, 2004. *Impact of Vacuum treatment on DGA*. ARS Altmann Group. http://www.ars-altmann.com/pubdoc/chromatografy 2004 e.pdf.

Aragón et. al., 2007: J. Aragón P., M. Fischer, S. Tenbohlen, 2007. *Improvement of dissolved gas analyses (DGA) by means of experimental investigation of generated fault gases and a fuzzy logic based interpretation scheme*. Proceedings of the 15th International Symposium on High Voltage Engineering, Slovenia, paper no. T7-157.

Aragón et. al., 2007: Aragón P. J., Tenbohlen S., Bräsel E., Sasum U., 2007. *Improved Monitoring of Dissolved Transformer Gases on the Basis of a Natural Internal Standard (NIS)*. Cigre A2/D1 Colloquium, Belgium.

Arvidsson, 2001: Arvidsson Lars, 2001, *Chemistry in Electrical Apparatuses*, Västeras Petrolumkemi AB, Sweden.

ASTM D 3612, 2004: ASTM International Standard, 2004. *Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography*, Annual Book of ASTM Standard, Vol. 10.03.

ATKINS, et. al., 2006: Atkins P. and Paula J. De., 2006. *Atkins' Physical Chemistry*, Oxford University Press, Oxford, UK.

Battino et. al., 1965: Rubin Battino, H. Lawrence Clever. *The Solubility of Gases in Liquids*. Illinois Institute of Technology, Chicago, Illinois, Received October 25.

Benner et. al., 1982: Benner C.O., Myers J.E., 1982. *Momentum, heat and mass transfer*. 3rd Edition. MacGraw-Hill, New York.

Borsi et. al., 1999: Borsi H., Dumke K., Gockenbach E., 1999. *Relationship between faults and generated gases in transformer liquids*. Proceedings of 13th International Conference on Dielectric Liquids, Japan.

Borsi et. al., 1999: Borsi, H., K. Dumke, E. Gockenbach, 1999. *Relationship between faults and generated gases in transformer liquids*. Proceedings on the 13th International Conference on Dielectric Liquids, Nara, Japan.

Cargol, 2005: Tim Cargol, 2005. *An overview of online oil monitoring technologies*. Fourth Annual Weidmann-ACTI Technical Conference, San Antonio, U.S.A..

Coates et. al., 1986: John P. Coates Lynn C. Setti, 1986. *Infrared Spectroscopic Methods for the Study of Lubricant Oxidation Products*, A S L E Transactions, 29:3, pp. 394-401

Coates et. al., 2008: Coates John P. and Lynn C. Setti, *Infrared spectroscopic methods for the study of lubricant oxidation products*. ASLE Transactions, 29:3, pp 394-401.

Danikas, 1993: Danikas M., 1993. *The Definitions used for Partial Discharge Phenomena*. IEEE Transactions on Electrical Insulation Vol. 28, No. 6, pp. 1075-1080

Dumke et. al, 1998: K. Dumke, H. Borsi, E. Gockenbach, 1998. *Influence of stressing on gaseous decomposition products in insulating liquids*. Conference Record, IEEE International Symposium on Electrical Insulation, USA.

Dumke et. al., 1996: K. Dumke, H. Borsi, E. Gockenbach, 1996. *Experimental investigations on the behavior of decomposition gases in insulating liquids caused by partial discharge and breakdown*. 12th International Conference on Conduction and Breakdown in Dielectric Liquids, Italy.

Dumke, 1999: K. Dumke, 1999. *Untersuchungen an einer Esterflüssigkeit als Isolierstoff für Transformatoren*. VDI Verlag GmbH, Düsseldorf. Germany ISBN 3-18-327321-7.

Duval et. al., 2001: M. Duval, A. dePablo, 2001. *Interpretation of Gas-In-Oil Analysis Using New IEC Publication 60599 and IEC TC 10 Databases*. IEEE Electrical Insulation Magazine, Vol. 17, Issue 2, pp. 34-37.

Duval, 1989: Duval, M., 1989. *Dissolved Gas Analysis: It can save your transformer*. IEEE Electrical Insulation Magazine, Vol., 5 (6).

Duval, 2002: Duval M., 2002. *A Review of Faults Detectable by Gas-in-Oil Analysis in Transformers*. IEEE Electrical Insulation Magazine, Vol. 18 (3).

Duval, 2005: Duval M., 2005. *Improving the Reliability of Transformer Gas-in-Oil Diagnosis*. IEEE Electrical Insulation Magazine, Vol. 21 (4).

Drews, 1998: Drews A. W., 1998. *Manual on hydrocarbon analysis*. ASTM International, 6th edition, pp. 20.

EL-Sayed, 2009: EL-Sayed M. M., EL-Refaie, Mohamed R. Salem, and Wael A. Ahmed, 2009. *Prediction of the Characteristics of Transformer Oil under Different Operation Conditions*. World Academy of Science, Engineering and Technology, Issue 53.

Fischer and Tenbohlen, 2009: Fischer M. and Tenbohlen S., 2009. *Improved condition assessement by fuzzy-modelling, adjustment and merging of DGAs Interpretation methods*. Proceedings of the 16th International Symposium on High Voltage Engineering, Johannesburg, 2009.

Florkowska et. al., 1999: Florkowska B. and Zydron P., 1999. *The Correlation of PD-Charge and Energy Patterns in the Study of Partial Discharge Mechanism in Thermostatting Insulation*. High Voltage Engineering Symposium, 22-27, Conference Publication No 467.

Fofana et. al., 2007: Fofana, I., Borsi, H., Gockenbach, E. and Farzaneh, M., 2007. *Aging of transformer insulating materials under selective conditions*. European Transactions in Electrical Power, Vol. 17, pp. 450470.

Fofana et. al., 2008: Fofana, I.; Sabau, J.; Bussieres, D.; Robertson, E.B., 2008. *The mechanism of gassing in power transformers*. IEEE International Conference on Dielectric Liquids, 2008. pp.1-4.

Foster, 1990: E. O. Forster, 1990. *Progress in the Field of Electric Properties of Dielectric Liquids*. IEEE Transactions on Electrical Insulation Vol. 25, No. 1, pp. 45-53.

Fruth et. al., 1992: Fruth, B.; Niemeyer, L., 1992. *The importance of statistical characteristics of partial discharge data*. IEEE Transactions on Electrical Insulation, Vol.27, no.1, pp.60-69.

Gaffuri et. al., 1997: Gaffuri, P., Faravelli, T., Ranzi, E., Cernansky, N. P., Miller, D., d'Anna, A. and Ciajolo, A. (1997). *Comprehensive kinetic model for the low temperature oxidation of hydrocarbons*. American Institute of chemical engineers (AIChE) Journal, Vol. 43, pp. 12781286.

Gibeault, 1997: Gibeault J.P., 1997. *On-line monitoring of key fault gases in transformer oil: an operational experience accumulated over the years*. 10th International Symposium on High Voltage Engineering (I.H.S.), Canada.

Gradnik, 2002: K. M. Gradnik, 2002. *Physical-chemical oil tests, monitoring and diagnostic of oil-filled transformers*. Proceedings of 14th International Conference on Dielectric Liquids, Austria.

Gradnik, 2007: M. K. Gradnik, 2007. *Transformer oil quality assurance in new high voltage transformers*. Proceedings of the15th International Symposium on High Voltage Engineering, Slovenia, paper no. T6-775.

Griffin, P. J., 1998: H.G. Erdman, 1988. *Criteria for the Interpretation of data for dissolved gases in oil from transformers*. Electrical Insulating oils, STP 998, pp. 89-106

Guo et. al., 2003: Guo Z.; N. F. Roache, 2003. *Overall mass transfer coefficient for pollutant emissions from small water pool under simulated environmental conditions*. Oxford Journals, Life Sciences Medicine, The Annals of Occupational Hygiene, Vol. 47, Issue 4, pp. 279-286.

Harlow, 2004: James H. Harlow, 2004. *Electric power transformer engineering*. Editorial CRC Press LLC, U.S.A. ISBN 0-8493-1704-5.

Heathcote, 1998: Heathcote J. M, 1998. *The J P Transformer Book*, Newness, U.K., ISBN 07506 1158 8.

Höhlein, 2006: Ivanka A. Höhlein, 2006. *Unusual Cases of Gassing in Transformers in Service*. IEEE Electrical Insulation Magazine, Vol. 22 (1), pp.2427, Germany.

IEC 60567, 2005: International Electro-technical Commission, 2005. *Guide for the sampling of gases and of oil from oil-filled electrical equipment and for the analysis of free and dissolved gases*.

IEC 60599, 1999: International Electro-technical Commission, 1999. *Mineral oil-impregnated electrical equipment in service. Guide to the interpretation of dissolved and free gases analysis*, IEC 60599.

Ioffe et. al., 1984: B. V. Ioffe; A. G. Vitenberg, 1984. *Head-Space Analysis and Related Methods in gas Chromatography*. Wiley-Interscience publication, U.S.A. ISBN 0-471-06507-2.

Jakob et. al., 2012: Jakob, F.; Noble, P.; Dukarm, J.J., 2012. *A Thermodynamic Approach to Evaluation of the Severity of Transformer Faults*. IEEE Transactions on Power Delivery, Vol.27, no.2, pp.554-559

Kelman Transport X GE Energy, Kelman Products. *Handling Manual: Transport X, portable DGA (Dissolved gas analysis)*.Version 1.4, 40-0086-01.

Khaled et. al., 2009: Khaled Shaban, Ayman EL-Hag and Andrei Matveev, 2009. *Predicting Transformers Oil Parameters*. IEEE Electrical Insulation Conference, Montreal, Canada.

Khaled, 2009: Khaled Shaban, Ayman EL-Hag and Andrei Matveev, 2009. *Predicting Transformers Oil Parameters*. IEEE Electrical Insulation Conference, Montreal, Canada, pp. 196-199.

Krawiec, 2009: Steve Krawiec, 2009. *Review of recent changes to mineral insulating oil specifications*. Electrical Insulation Conference, 2009. IEEE, pp. 363 367

Leblanc et. al., 1993: Y. Leblanc, R. Gilbert, M. Duval, and J. Hubert, 1993. *Static headspace gas chromatographic determination of fault gases dissolved in transformer insulating oils*. Journal of Chromatography, Vol. 633, pp.185-193.

Lipscomb, 1988: T. G. Lipscomb, 1988. *Mineral Insulating oil manufacture and safekeeping*. Electrical Insulating oils, H.G. Erdman, Ed., American Society for testing and materials, U.S.A., pp. 5-24.

Lipshtein et. al., 1970: Lipshtein R.A. and M. Shakhnovich, 1970. *Transformer oil*. 2nd edition, Israel Program for Scientific Translation, Jerusalem.

Masunov et. al., 2001: A. Masunov, J. Dannenberg, R. Contreras, 2001. *C-H Bond-Shortening upon Hydrogen Bond Formation: Influence of an Electric Field*. Journal of Physical Chemistry, 105, pp. 4737 4740.

Möllmann et. al., 1999: Möllmann, A. and Pahlavanpour, B. (TF 15.01.01), 1999. *New guideline for interpretation of dissolved gas analysis in oil filled transformers*. Electra, No. 186, pp. 31-51.

Mori et. al., 1999: E. Mori, H. Tsukioka, K. Takamoto, N. Miyamoto, T. Kobayashi, S. Kobayashi and H. Okubo, 1999. *Latest Diagnostic Methods of Gas-in-Oil Analysis for Oil-filled Transformer in Japan*. Proceedings of the 13th International Conference on Dielectric Liquids (ICDL 99), Japan.

Muhr et. al., 2006: M. Muhr, R. Schwarz, 2006. *Partial discharge measurement as a Diagnostic Tool for HV-Equipments*. Properties and applications of Dielectric Materials, 2006. 8th International Conference on, IEEE, pp.195-198.

Murphy, 1970: Murphy E. J., 1970. *The generation of gases in the dielectric breakdown of oil*. J. Phys. D: Appl. Phys. Vol. 3, pp. 917-923.

NCho et. al., 2011: NCho J. S., I. Fofana, A.Beroual, T. Aka-Ngnui and J. Sabau, 2011. *The gassing tendency of various insulating fluids under electrical discharge*. IEEE Trans. Elec. Insul., Vol. 18, pp 1616-1625

Narang et. al., 2012: Ena Narang, Er. Shivani Sehgal, Er. Dimpy Singh, 2012. *Fault detection techniques for transformer maintenance using dissolved gas analysis*. International Journal of Engineering Research Technology (IJERT).Vol. 1 Issue 6.

Nelson, 1969: Nelson W. L., 1969. *Petroleum Refinery Engineering*. McGraw Hill, 4th Edition, Toronto, p. 744.

Nynäs Naphthenics, 2004: Nynäs Naphthenics AB, 2004. *Transformer oil handbook*, Sweden, ISBN no: 91-631-4982-6.

Sabau et. al., 2000: John Sabau and Rolf Stokhuyzen, 2000. *The Side Effects of Gassing in Transmission Power Transformers*. IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp. 264-267.

Sangui, 2003: Sanghi, R., 2003. *Chemistry behind the life of a transformer*. Resonance Magazine, Vol. 8(6), pp. 17-23

Schmidt, 1982: Schmidt, W.F., 1982. *Elementary Processes in the Development of the Electrical Breakdown of Liquids*. IEEE Transactions on Electrical Insulation, Vol.EI-17, no.6, pp.478-483.

Scott et. al., 2002: Scott A. S. and G. H. Jirka, 2002. *Environmental fluid mechanics Part I: Mass transfer and diffusion*. 2nd Edition, Institut für Hydromechanik, Universität Karlsruhe, Germany.

Sherif, et. al, 2012: Sherif S. M. Ghoneim, Sayed A. Ward, 2012. *Dissolved Gas Analysis as a Diagnostic Tools for Early Detection of Transformer Faults*. Advances in Electrical Engineering Systems (AEES) Vol. 1, No. 3, pp. 152-156.

Shirai et. al., 1997: Shirai, M.; Ishii, T.; Makino, Y., 1977. *Evolution of Hydrogen from Insulating Oil in Transformers*. IEEE Transactions on Electrical Insulation, Vol.EI-12, no.4, pp. 266-272

Shirai et. al., 1997: Shirai, M.; Shimoji, S.; Ishii, T., 1977. *Thermodynamic Study on the Thermal Decomposition of Insulating Oil*. IEEE Transactions on Electrical Insulation, Vol. EI-12, no. 4, pp. 272-280.

Sing et. al., 2010: Sukhbir Sing, M.N. Bandyopadhyay, 2010. *Duval Triangle: A Noble Technique for DGA in Power Transformers*. International Journal of Electrical and Power Engineering, Vol. 4, pp. 193-197

Sokolov, et. Al., 2001: Sokolov, V.; Bulgakova, V.; Berler, Z., 2001. *Assessment of power transformer insulation condition*," Proceedings Conference on Electrical Insulation Conference and Electrical Manufacturing Coil Winding, pp.605-613

Sokolov, et. Al., 2001: Sokolov V., Berler Z. and Rashkes V., 1999. *Effective methods of assessment of insulation system condition in power transformers: A view based on practical experience*. Proceedings Conference on Electrical Insulation Conference and Electrical Manufacturing Coil Winding, pp.659 -667

Sun et. al., 2012: Huo-Ching Sun, Yann-Chang Huanga, Chao-Ming Huangb, 2012. *A Review of Dissolved Gas Analysis in Power Transformers*. Energy Procedia 14, pp. 1220 1225

Tenbohlen, 2004: S. Tenbohlen, 2004. *New Concepts for Prevention of Ageing by Means of On-line Degassing and Drying and Hermetically Sealing of Power Transformers*. CIGRE, Paris, paper A2-204.

TD-World, 2007: TD-World, 2007. *Company provides transformer monitoring for aging equipment*. Transmission and Distribution World 2007, Prism Business Media, March 5, 2007.

Van Brunt, 1994: Van Brunt, R.J., 1994. *Physics and Chemistry of Partial Discharge and Corona*, Recent Advances and Future Challenges. IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 1(5).

Wang et. al., 2012: Zhongdong Wang; Xiao Yi; Jinping Huang; Hinshaw; J.V., Noakhes, J., 2012. *Fault gas generation in natural-ester fluid under localized thermal faults*. IEEE Electrical Insulation Magazine, Vol. 28, no. 6, pp. 45-56.

Yokozeti, 2002: A. Yokozeki, 2002. *Time-dependent behavior of gas absorption in lubricant oil*. International Journal of Refrigeration, Vol. 25, pp. 695704

Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit mit dem Titel:

„Experimental Investigations on the Dissolved Gas Analysis Method (DGA) through Simulation of Electrical and Thermal Faults in Transformer Oil"

selbst verfasst und keine außer den angegebenen Hilfsmitteln und Quellen benutzt habe, und dass die Arbeit in dieser oder ähnlicher Form noch bei keiner anderen Universität eingereicht wurde.

Essen, dem 14.03. 2014

Jackelyn Aragón Gómez

Publikationen

J. Aragón, M. Fischer, S. Tenbohlen: "*Interpretation der Gas-in-Öl-Analysen von Leistungstransformatoren durch Einsatz von Fuzzy Logik mit dem Ziel einer präziseren IT-gestützten Zustandserfassung"*, ETG Fachtagung "Diagnostik elektrotechnischer Betriebsmittel", Germany, 19.-20. September, 2006.

J. Aragon, M. Fischer, S. Tenbohlen: *"Improvement of interpretation of dissolved gas analysis for power transformers"*, International Conference APTADM, Wroclaw, Poland, 2007.

J. Aragón, M. Fische, S. Tenbohlen: *"Improvement of dissolved gas analysis (DGA) by means of experimental investigations of generated fault gases and a fuzzy logic based interpretation scheme"*, 15th International Symposium on High Voltage Engineering, ISH, Ljubljana, Slovenia, 2007.

J. Aragon, S. Tenbohlen: *"Improved Monitoring of Dissolved Transformer Gases on the Basis of a Natural Internal Standard (NIS)"*, CIGRE Colloquium, Belgium, 2007.

J. Aragón, M. Fischer, S. Tenbohlen, M. Schäfer, Z. D. Wang, I. Höhlein Atanasova: *"Investigation on Sampling, Measurement and Interpretation of Gas-in-Oil Analysis for Power Transformers"* CIGRE Session, Paris, France, 2008.

Curriculum Vitae

"The CV is not included in the online version for reasons of data protection."